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REPORT NO. 710/409

BALLISTIC AND METALLURGICAL PROPERTIES OF HIGH ALLOY FACE HARDENED ARMOR PLATE MADE BY THE PLURAMELT PROCESS

by

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February 11, 1942

WATERTOWN ARSENAL
WATERTOWN, MASS.

Report No. 710/409
Watertown Arsenal
(Ex. O. 51-A21,1941)

February 11, 1942

Ballistic and Metallurgical Properties of High Alloy Face Hardened Armor Plate Made by the Pluramelt Process

OBJECT

To determine the ballistic and metallurgical properties of Pluramelt, (a composite armor plate) including chemical analysis, macroscopic and microscopic examination, and hardness surveys.

REFERENCES

O.O. 470.1/1069 W.A. 470.1/5178

The basic correspondence and material pertaining to this report are contained in Appendix A.

CONCLUSIONS

1. High alloy face hardened armor plate (.35/.40 carbon, 12/13 chrome face; .06/.08 carbon, 12/13 chrome back) made by the Pluramelt Process is not suitable for good quality armor plate for the following reasons:

a. Spalling of front face and occasionally back spalling. Of forty-two (42) Pluramelt plates tested at Aberdeen Proving Ground, only seven (7) passed. (See Table II.)

b. Poor flame cutting properties.

c. Exceptionally high chromium content.

2. Metallurgical examination showed the following defects in the material:

a. Pronounced bands of carbides and some grain boundary carbides in the hard surface layer. (See Figures 11a, b, 16a, b, and 17a, and 18a.)

b. Elongated nonmetallic inclusions which were associated with crack systems in the hard surface layer. (See Figure 8.)

c. Some grain boundary carbide in the junction of the hard surface layer and the steel base. (See Figures 17b, and 18c.)

d. Occasionally some grain boundary carbide was found in the steel base. (See Figures 16d, 17c, and 18d.)

3. Metallurgical examination indicated that the steel base was relatively free from nonmetallics and that with one exception, a gradual transition in microstructure was evident from the hard surface layer to the steel base. (See Figures 7a, 12, 14, 15, and 10b.)

4. The high chromium Pluramelt may be heat treated satisfactorily by normalizing only.

5. Pluramelt of a new composition (surface layer containing approximately 0.40% carbon, 5% nickel, and steel base containing approximately .20% carbon, and 5.0% nickel) has shown promising ballistic properties. (See Table III.)

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INTRODUCTION

In April 1940, representatives from the Allegheny Ludlum Steel Corporation discussed with the technical staff at Watertown Arsenal a cooperative program covering the metallurgical examination and ballistic tests of various samples of Pluramelt. Accordingly, samples 1/8" and 1" thick were submitted for investigation as follows:

Plate No.	Size	
AR30	1"x36"x36"	welded plate 2 sections examined - noted as "B" & "C"
AR35	1"x36"x36"	
AR36	1/8"x12"x12"	
AR37	1/8"x12"x12"	
AR38	1/8"x12"x12"	
AR39	1/8"x12"x12"	

The explanation of the Pluramelt Process in some detail is given in Appendix A.

TEST PROCEDURE

1. Ballistic Tests

Ballistic tests were made on the 1/8" thick material at Watertown Arsenal while the 1" thick plates were tested at Aberdeen Proving Ground.

2. Metallurgical Examination

a. Chemical Analysis

Chemical analysis was made on the surface hardened layer and also on the back face of the plates after they were annealed by heating to 1500°F for one hour and cooling in the furnace.

b. Macroscopic Examination

Longitudinal and transverse sections cut from the plates were etched in Oberhoffer's reagent and in the standard Watertown Arsenal macroetching acid mixture containing -

12 parts by volume conc H_2SO_4 SpGr 1.8
36 " " " " HCL " 1.1
50 " " " H_2O

c. Microscopic Examination

Microscopic examination was made on the surface hardened layers, at the junction of the face hardened surface and steel base and also on the steel base of the various samples submitted.

d. Physical Tests

Physical tests were made on the steel base of the 1" thick plate, No. AR35.

e. Hardness Surveys

Vickers Brinell hardness surveys were made on sections cut from the plates to show the variation in hardness from the surface to the rear face.

RESULTS OF TESTS

1. Ballistic Tests

a. Ballistic Properties of Plates Examined at Watertown Arsenal

The ballistic tests were made at Aberdeen Proving Ground and at Watertown Arsenal and the results of these tests are recorded in Table I as follows:

Plate AR30 - A.P.G. Partial Report No. 156, dated January 5, 1940.
Plate AR35 - A.P.G. Partial Report No. 179, dated February 26, 1940.
Plates AR36, AR37, AR38, AR39 - W.A. Letter Report dated May 28, 1940 covering W.A. Ballistic Reports 115/134, 115/135, 115/136, and 115/137.

Table I

Ballistic Tests

Plate	Round No.	Ammunition	Striking Velocity F/S	Remarks
AR30 1"x36"x36"	1	37mm. A.P. M39	1796	Complete penetration on plate 2½" above weld. Shattered plate below weld.
	2	"	1790	Complete penetration on plate above weld; 4-3/4" spall.
Note: Plate resisted Cal. .50 A.P. M1, striking velocity 2969 f/s (highest partial). Plate tested under Spec. AXS-54K-2 was unsatisfactory when subjected to shock test with 37mm. Resistance to penetration of plate satisfactory.				
AR35 1"x36"x36"	1	37mm. A.P. M39	1909	Complete penetration, face spall 5-3/8"x3-1/9".
	2	"	1906	Complete penetration.
Note: Plate resisted Cal. .50 A.P. M1, striking velocity 3053 f/s (highest partial). Plate tested under Spec. AXS-54K-2 was satisfactory.				
AR36 1/8"x12"x12"	1	Cal..30 A.P. M1922	1200	Complete penetration, clean cut hole, no cracks.
	2	"	1000	Complete penetration, clean cut hole, no cracks.
	3	"	2600	Complete penetration, irregular hole, approximately 1/2"x5/8"; two small cracks, front and back.
	4	Cal..30 Ball Service	2600	Complete penetration, irregular hole, 3/4"x7/8"; two small cracks, front and back.
AR37 1/8"x12"x12"	1	Cal..30 A.P. M1922	1000	Complete penetration,clean cut hole, no cracks.
	2	"	1000	Complete penetration,crack at penetration both faces.
	3	Cal..30 Ball Service	2600	One small crack at penetration front and rear face.

Table I (Cont'd)

Plate	Round No.	Ammunition	Striking Velocity F/S	Remarks
AR37 1/8"x12"x12"	4	Cal..30 A.P. M1922	2600	Complete penetration, hit round 3. Some circular cracks at impact. Irregular hole about 3/4"x7/8".
	5	Cal..30 Ball Service	2600	Complete penetration, irregular hole about 3/4"x7/8"; small cracks at front and rear face.
	6	Cal..30 A.P. M1922	2600	Complete penetration, irregular hole about 3/8"x1/2". Small surface crack.
AR38 1/8"x12"x12"	1	Cal..30 A.P. M1922	1000	Partial penetration, no cracks, slight indentation.
	2	"	1000	Complete penetration, clean cut hole.
	3	"	1200	Complete penetration, clean cut hole.
	4	"	1000	Complete penetration, clean cut hole.
	5	"	1000	Complete penetration, clean cut hole.
	6	Cal..30 Ball Service	2600	Complete penetration, irregular hole, 1/2"x5/8". Circular cracks on surface.
	7	Cal. .30 A.P. M1922	2600	Complete penetration, irregular hole, 1/2"x3/8".
AR39 1/8"x12"x12"	1	Cal. .30 A.P. M1922	1000	Partial penetration; punching started, no cracks.
	2	"	1000	Complete penetration; clean cut hole, no cracks.
	3	"	1000	Complete penetration; clean cut hole, no cracks.
	4	Cal. .30 Ball Service	2600	Complete penetration. Irregular hole 5/8"x1/2". Circular cracks at impact.
	5	Cal..30 A.P. M1922	2600	Complete penetration. Irregular hole 5/8"x1/2". Circular cracks at impact. Small particles blown from back.

Table I (Cont'd)

Note: Penetration occurred on Plates AB36, AB37, AB38, and AB39 at a striking velocity below that required by Spec. AXS-54K-Rev.3 (requirements 1590 f/s, Cal. .30 A.P. by extrapolation).

b. Resume of Ballistic Tests on Pluramelt at Aberdeen Proving Ground

The resume of ballistic tests made on high chromium Allegheny Ludlum Pluramelt at Aberdeen Proving Ground (reference, A.P.G. Partial Reports 156, 179, 204, 215, 226, 256, 286, and 310) are shown in Table II.

Table II

Resume of Ballistic Tests

Plate Thickness	Good Plates	Bad Plates	Total
1/8"	0	4	4
1/4"	2	7	9
3/8"	1	3	4
1/2"	1	5	6
1"	3	4	7
1-1/2"	0	4	4
2"	0	8	8
	7	35	42

c. Ballistic Tests of 5% Nickel Pluramelt

Ballistic tests made on the new 5% nickel Pluramelt as reported by Allegheny Ludlum Company are given in Table III.

Table III

Ballistic Properties of Allegheny Pluramelt Armor Plates

July 3, 1941

Heat No.	Thick-ness	Brinell Hardness Face	Brinell Hardness Back	Ammunition	Lowest Complete	Result# Table 1	Result# Table 2
43494-4	3/16"	578	460	.30 Cal. M-2	2001 HP*	OK	OK
43494-6	3/16	600	444-460	.30 Cal. M-2	2112	OK	OK
43301-11	1/4	532	444	.30 Cal. M-2	1916	F	F
AR-155	1/4	578	444	.30 Cal. M-2	2140	OK	OK
AR-156	1/4	600-627	444	.30 Cal. M-2	2271	OK	OK
43486-13	1/4	532	444	.30 Cal. M-2	1967	F	F
43494-2	1/4	578	444	.30 Cal. M-2	2269	OK	OK
43494-5	1/4	600	477	.30 Cal. M-2	2077 HP	OK	OK
43494-11	1/4	578-652	460-477	.30 Cal. M-2	2145 HP	OK	OK
43494-12	1/4	578	444-460	.30 Cal. M-2	2081	OK	OK
43301-14	5/16	578	444	.30 Cal. M-2	2278	OK	OK
43301-14	5/16	600	460-477	.30 Cal. M-2	2311	OK	OK
43408-12	5/16	600	444-460	.30 Cal. M-2	2028**	F	F
43538-10	5/16	600	477	.30 Cal. M-2	2164**	F	F
43301-3-2	3/8	600	444-460	.50 Cal. M-1	1957	OK	OK
43301-3-2	3/8	613	477	.50 Cal. M-1	1908	OK	OK
43301-10	3/8	600	460-477	.50 Cal. M-1	1931 HP	OK	OK
43301-13	3/8	578-600	444	.50 Cal. M-1	1942 HP	OK	OK
43408-1-2	3/8	600	444	.50 Cal. M-1	2162 HP	OK	OK
43408-1-2	3/8	627	444	.50 Cal. M-1	1930 HP	OK	OK
43408-2-2	3/8	627	477	.50 Cal. M-1	2130 HP	OK	OK
43408-2-2	3/8	613	477	.50 Cal. M-1	2098 HP	OK	OK
43408-9	3/8	600	460-477	.50 Cal. M-1	1903 HP	OK	OK
43486-3	3/8	532	444	.50 Cal. M-1	1786	F	F
43486-3	3/8	600	444-477	.50 Cal. M-1	1912 HP	OK	OK
43486-2	3/8	578	444-460	.50 Cal. M-1	1892	OK	OK
43486-3	3/8	570	444	.50 Cal. M-1	1846	OK	F
43486-15	3/8	600	444	.50 Cal. M-1	1826	OK	F
43494-1	3/8	600	477	.50 Cal. M-1	1874 HP	OK	OK
43494-6	3/8	600	460	.50 Cal. M-1	1903 HP	OK	OK
43494-13	3/8	600	444	.50 Cal. M-1	1925 HP	OK	OK
43494-13	3/8	600	444-460	.50 Cal. M-1	1942 HP	OK	OK
43511-13	3/8	578-600	444-460	.50 Cal. M-1	1981 HP	OK	OK
43511-16	3/8	600	460-477	.30 Cal. M-2	2447	OK	OK
AR-154	1/2	555-578	444	.50 Cal. M-1	2304	OK	OK
43301-3-3	1/2	627	444	.50 Cal. M-1	2179	OK	OK
43408-2-3	1/2	627	460	.50 Cal. M-1	2221	OK	OK

*HP - Highest Partial Penetration

**Impacts irregular, one showed complete penetration at velocity of 2028 ft/s, others showed completes at 2263-2311 and partials at 2263-2319.

***Impacts irregular, one showed complete penetration at velocity of 2164 ft/s, others showed partials at 2204-2067 and 2379.

#See Specification O.S. No. 595, Tables I and II.
F = Failed

2. Metallurgical Examination

a. Chemical Analyses

Chemical analyses of the Pluramelt plates are given in Table IV.

Table IV

Plate No.	C	Mn	P	S	Si	Ni	Cr
AR30 Face	.35	.15	.006	.016	.350	0.94	12.45
AR30 Rear	.07	.40	.015	.006	.365	1.10	12.28
AR35 Face	.45	.30	.012	.022	.765	.85	12.85
AR35 Rear	.06	.40	.010	.015	.400	.87	12.99
AR36, 37, 38, 39 Face	.29	.29	.007	.016	.500	1.06	12.15
AR36 Rear	.055	.23	.009	.023	.570	1.00	12.66

b. Macrostructure

(1) The macrostructure of the plates as revealed by the deep etch is described below:

Plate AR30 Welded Plate

Section B - The metal near the top and bottom surfaces is quite clean and shows a fine and uniform macrostructure. In the central portion, there are a few scattered laminations.

Sample 2 was cut at right angles to section 1.

Section C - The metal in this plate is similar near the top and bottom surfaces to that described for plate B but the central portion is heavily laminated and contains some etched-out impurities.

Sample 2 was cut at right angles to section 1.

Plate AR35

The face of the plate shows quite prominent well-distributed pits after etching. The fusion between the face and the base layers

Table I

Ballistic Tests

Plate	Round No.	Ammunition	Striking Velocity f/s	Remarks
AR30 1"x36"x36"	1	37mm. A.P. M39	1796	Complete penetration on plate 2½" above weld. Shattered plate below weld.
	2	"	1790	Complete penetration on plate above weld; 4-3/4" spall.

Note: Plate resisted Cal. .50 A.P. M1, striking velocity 2969 f/s (highest partial). Plate tested under Spec. AXS-54K-2 was unsatisfactory when subjected to shock test with 37mm. Resistance to penetration of plate satisfactory.

Plate	Round No.	Ammunition	Striking Velocity f/s	Remarks
AR35 1"x36"x36"	1	37mm. A.P. M39	1909	Complete penetration, face spall 5-3/8"x3-1/9".
	2	"	1906	Complete penetration.

Note: Plate resisted Cal. .50 A.P. M1, striking velocity 3053 f/s (highest partial). Plate tested under Spec. AXS-54K-2 was satisfactory.

Plate	Round No.	Ammunition	Striking Velocity f/s	Remarks
AR36 1/8"x12"x12"	1	Cal..30 A.P. M1922	1200	Complete penetration, clean cut hole, no cracks.
	2	"	1000	Complete penetration, clean cut hole, no cracks.
	3	"	2600	Complete penetration, irregular hole, approximately 1/2"x5/8"; two small cracks, front and back.
	4	Cal..30 Ball Service	2600	Complete penetration, irregular hole, 3/4"x7/8"; two small cracks, front and back.
AR37 1/8"x12"x12"	1	Cal..30 A.P. M1922	1000	Complete penetration, clean cut hole, no cracks.
	2	"	1000	Complete penetration, crack at penetration both faces.
	3	Cal..30 Ball Service	2600	One small crack at penetration front and rear face.

b. Microstructure

The rear faces of plates AR30, AR35, AR36, AR37, AR38, and AR39 are relatively free from nonmetallic inclusions. (See Figure 7a.) The hard surface of plates AR30, AR36, AR37, and AR38 contains some fine stringers of nonmetallic inclusions but in general are fairly clean. (See Figure 7b.) The hard surface layers of plates AR35 and AR39 contain a relatively high percentage of elongated nonmetallic inclusions. (See Figures 7c and 7d.) A crack system in the hard surface layer of plate AR39 was found to be associated with a series of nonmetallics. (See Figure 8.) A considerable number of nonmetallics were present at the junction of the hard surface layer and the soft back of plate No. AR30 at several areas.

In most of the samples there is a gradual transition in the microstructure of the relatively high carbon surface to the low carbon rear face. (See Figures 9, 12, 14, and 15.) In the case of one section of plate AR30 this was not true. A sharp line of demarcation between the hard surface and soft back was detected. (See Figure 10.)

The high carbon layers of the plates consist of banded carbides in a martensitic matrix, while the microstructure of the steel bases of the plates consisted of chromium ferrite pools in a low carbon martensite matrix. (See Figures 9 - 16 inclusive.)

In the high carbon face of plates AR30, AR35, AR36, and AR39 considerable carbide banding was evident. (See Figures 9a, 11a, b, c, 12a, 13a, 15a, and 16c.) This banding was less noticeable in plates AR37, and AR38. (See Figure 14a.) In plate AR35, evidence of a wedge shaped ferrite streak is present in the hard surface layer. (See Figure 13b.) A prominent band of carbide is evident in the hard surface layer of plates AR36 and AR39. This band runs in the center of the layer, parallel to the surface of the sheet. (See Figure 18a.)

In the low carbon backs of the plates AR30, AR35, AR36, AR37, AR38, and AR39 the ferrite pools occur in distinct bands, an example of which is shown in Figure 9b. There is evidence of some decarburization on the hard surface of the plates examined as noted below:

Plate No.	Depth of Decarburization
AR30	.015"
AR35	.01"
AR36	.01"
AR37	.022"
AR38	.012"
AR39	.01"

The grain size of the outer hard layers and the rear faces of the plates is given below:

Plate No.	Grain Size A.S.T.M. No. Outer Hard Surface	Soft Back
AR30	7	3
AR35	less than 8	5-6
AR36	8 - 10	6-7
AR37	6	5-6
AR38	6	5-6
AR39	8 - 10	6-7

In the high carbon layers of plate AR39 and AR36, there is a progressive increase in grain size from the prominent band to the outer surface of the plate.

Fine grain boundary carbides are present in the low carbon layers of most of the plates as revealed by the Murakami reagent. (See Figures 17c and 18d.) Some prominent grain boundary carbide chains occur in the junction of the high and low carbon layers in plates AR35, AR36, AR37, AR38, and AR39. (See Figures 17b, and 18c.) Some medium size grain boundary carbides are present in this area in plate AR30. There are fine grain boundary carbides present in the hard surface layers of plates AR37, and AR38. Pronounced carbide bands are present in the high carbon face of plates

AR30, AR35, AR36, and AR39. (See Figures 16a, c, and 18a.) The Murakami etch shows that there is a more complete solution of carbide in the surface layer of plates AR37 and AR38 than in the other samples. Some evidence of bands of carbide are present in the steel base of plate AR35. (See Figure 16d.)

The thickness of the layers on the Pluramelt is given below:

Plate No.	Total Thickness Inches	High Carbon Outside Layer Inches	Low Carbon Back Layer Inches	Junction Inches
AR30	1.00	.189-.31	.811-.69	--
AR35	1.00	.35	.58	.07
AR36	.132	.052	.052	.022
AR37	.132	.054	.043	.035
AR38	.132	.036	.061	.035
AR39	.132	.064	.046	.022

c. Physical Tests

Physical tests made on the steel base of the plate AR35 are reported in Table V.

Table V

Plate No.	Y.S.P. .01% Set Lbs./Sq.In.	T.S. Lbs./Sq.In.	Elong. % in 1.4"	Cont. of Area %	Remarks
AR35-1	114,000	188,000	7.9	24.1	Fracture begins at small crack at outer edge. Irregular break. Small non-metallic streaks. Small gas cavities.
AR35-2	105,000	162,000	5.0	16.6	Irregular break, small nonmetallic areas. Fracture begins at small crack at outer edge. Large crack on stem.

Note: - Sample 2 cut at right angle to sample 1.

d. Hardness Surveys

(1) Brinell Hardness

Brinell hardness values as reported and determined at Watertown Arsenal are given below:

	Brinell Hardness			
	As Reported		Determined at Watertown Arsenal	
Plate No.	Face	Back	Face	Back
AR30-B			477	340
AR30-C			477	340
AR35	525	375	477	364

(2) Vickers Brinell Hardness Surveys

Vickers Brinell hardness surveys made on cross sections of the plates are shown in Figures 19-24 inclusive.

DISCUSSION

The results of this investigation indicate that the high chromium Pluramelt material is not suitable for good quality armor because of the spalling characteristics of the hard surface layer, poor flame cutting characteristics and the high chromium content.

It is claimed by the manufacturers that this type of Pluramelt can be heat treated to the proper hardness by normalizing only. Metallurgical examination on the plates submitted for this examination indicates that the normalizing treatment does not in all cases retain the carbides completely in solution in the hard surface layer and in many cases in the steel base. These segregated carbides in combination with elongated nonmetallics present in many of the plates may be contributing factors to failure.

It should be noted that of forty-two (42) Pluramelt plates tested at Aberdeen Proving Ground only seven plates passed. (See Table II.)

It is claimed that this type of Pluramelt welds satisfactory. In the case of the 1-inch plate AR30, the weld withstood the penetration test but the plate itself failed. (Reference, 156th Aberdeen Proving Ground Partial Report.)

Within the past year, the manufacturers of Pluramelt have developed another type of hard surface armor containing 5% nickel, with about 0.40% carbon in the surface and about 0.20% carbon in the steel base. Navy tests indicate that this is a promising material. (See Table III.)

Tests made at Watertown Arsenal indicate the material has good ballistic and shock resistance but there was a slight indication of brittleness on the rear face during the shock test.

Figures 1-6 inclusive illustrate the macrostructures of the high chromium Pluramelt.

Figures 7-18 inclusive show the microstructures of this material.

Figures 19-24 show the hardness surveys of Pluramelt plates of various thicknesses.

Figure 1

Macrostructure

Deep Etch

Plate AR30 - Welded Plate

Section B

The metal near the top and bottom surfaces is quite clean and shows a fine and uniform macrostructure. In the central portion, there are a few scattered laminations.

Sample 2 was cut at right angles to sample 1.

Section C

The metal in this plate is similar near the top and bottom surfaces to that described for Plate B, but the central portion is heavily laminated and contains some etched-out impurities.

Note the variation in thickness in the hard surface layers.

Sample 2 was cut at right angles to sample 1.

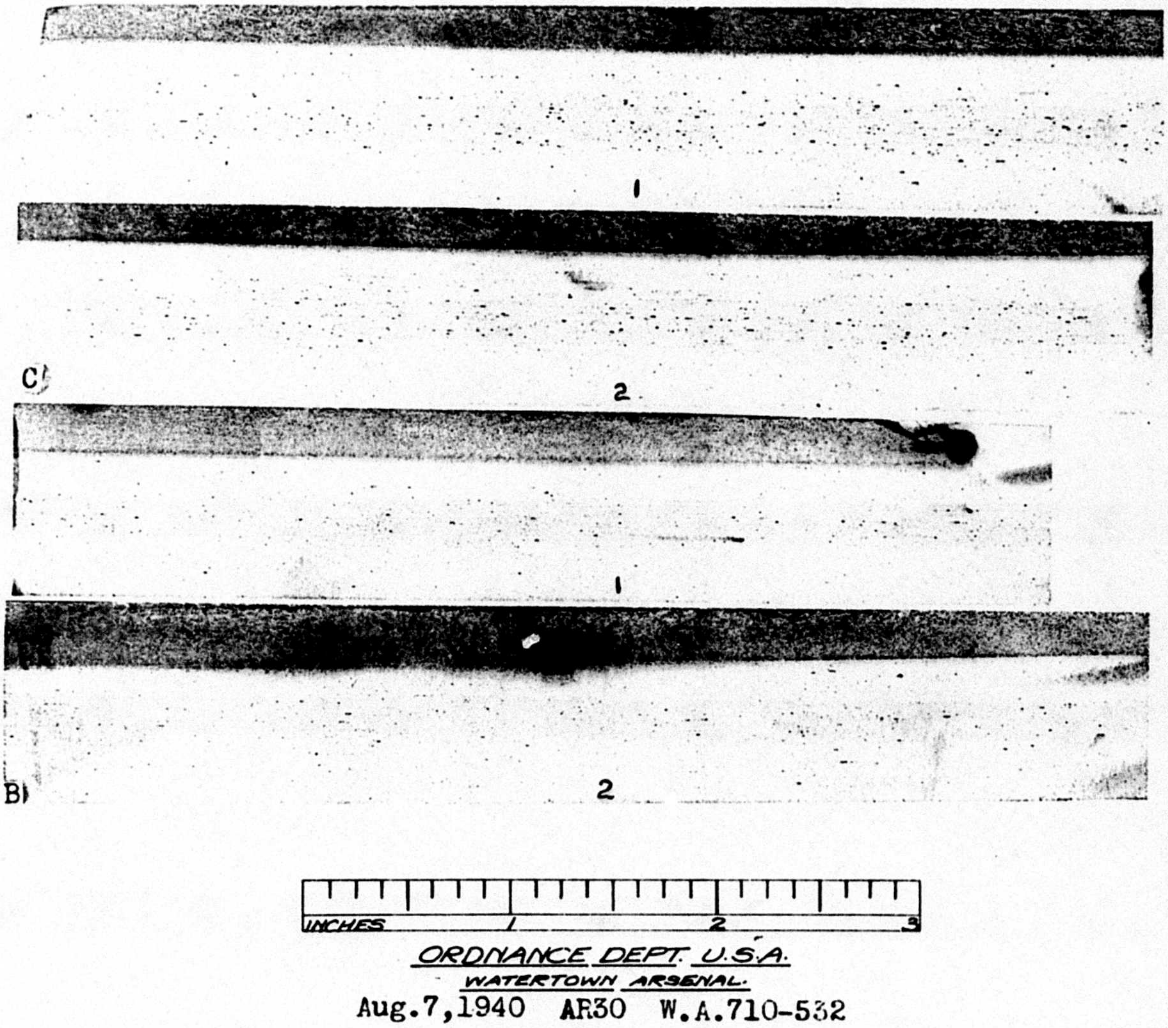

1
C
2
1
B
2
INCHES 1 2 3
ORDNANCE DEPT. U.S.A.
WATERTOWN ARSENAL.
Aug.7,1940 AR30 W.A.710-532

FIG 1

Figure 2

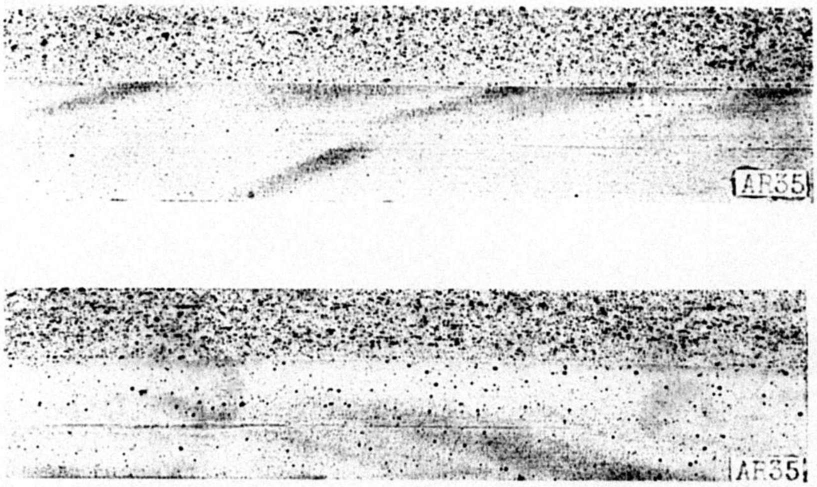
Macrostructure

Deep Etch

Plate AR35

The face of the plate shows quite prominent, well-distributed pits. The fusion between the top and the base sections appears to be quite uniform. The base metal shows fine laminations with a satisfactory amount of hot working. A few scattered impurities, now partially etched out, can be seen in this portion of the plate.

Sample 2 is cut at right angles to sample 1.



INCHES 1 2 3

ORDNANCE DEPT. U.S.A.

WATERTOWN ARSENAL.

May 24,1940 W.A.710- 445

Figure 2

Figure 3

Macrostructure

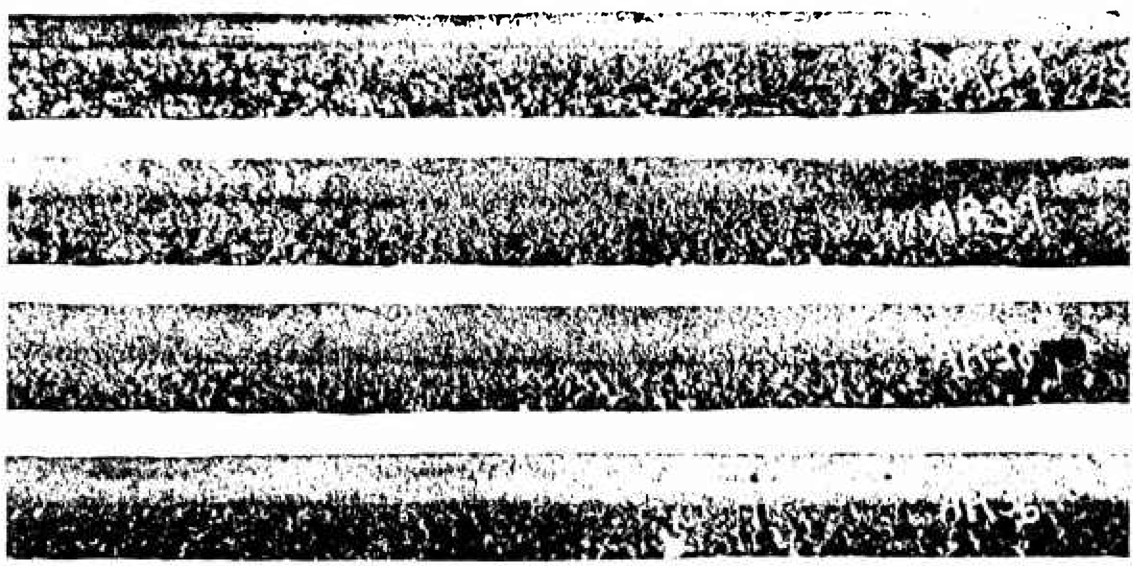
Deep Etch

Plates AR36, AR37, AR38, and AR39

Each of the plates submitted shows practically equal thicknesses of base metal and armor plate. The junction between the layers appears to be sound and uniform. In the hard zone, quite prominent etched-out segregates are found.

X5 MA-2077

Figure 3



W.A.639-3805

Figure 4

Macrostructure

Oberhoffer's Etch

Plate AR30 - Section B

The hard surface layer had a uniform structure. The steel base only showed a trace of banding. A sharp line of demarcation is observed between the hard surface and the steel base.

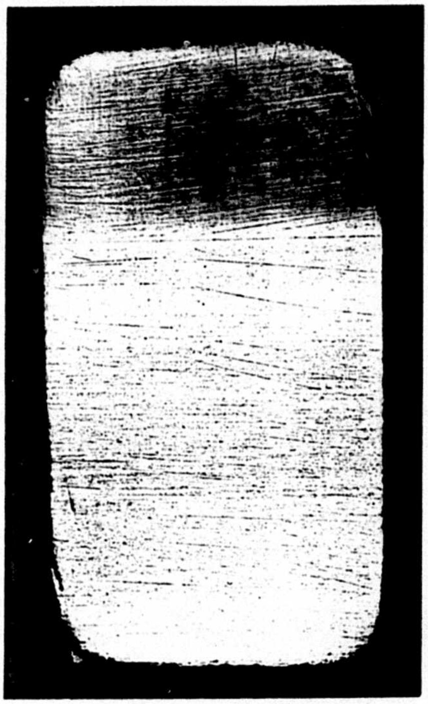
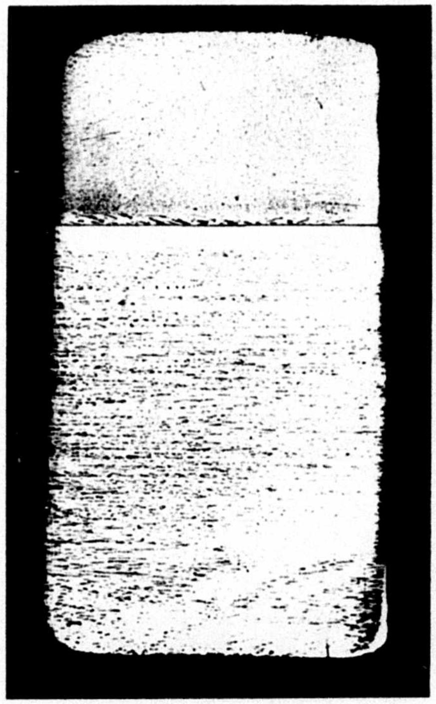
X3 MA-3194&MA-3195

Section C

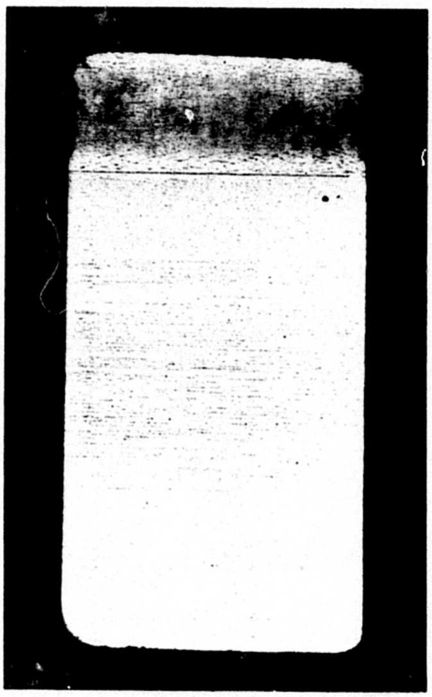
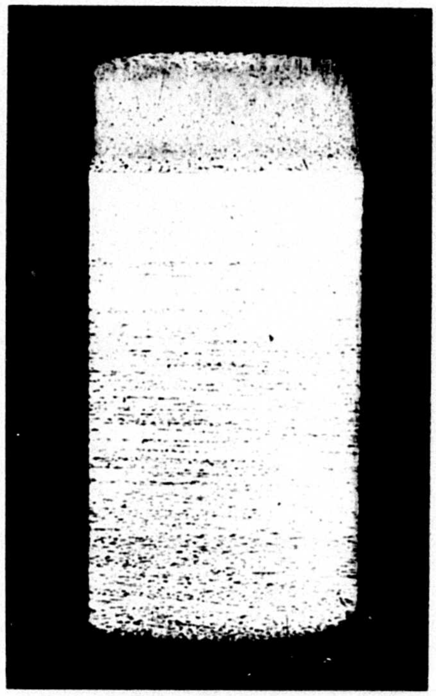
Same as section B.

X3 MA-3192&MA-3193

Figure 4

Longitudinal Section B Transverse

Longitudinal Section C Transverse

W.A.639-3806

Figure 5

Macrostructure

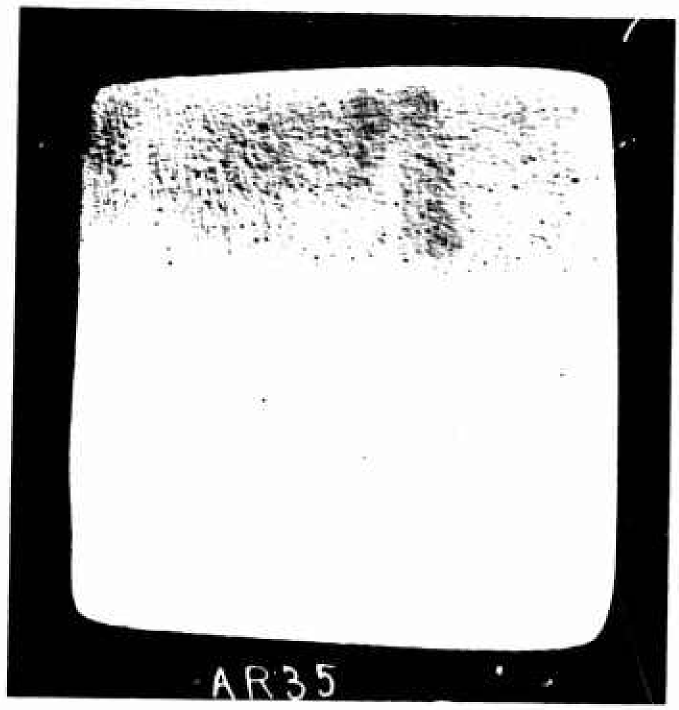
Oberhoffer's Etch

The junction between the hard surface layer and the steel base is clearly visible. No pronounced segregations are evident.

X3

MA-2013

Figure 5



W.A.6[illegible]-3307

Figure 6

Macrostructure

Oberhoffer's Etch

Plate AR36

Slight banding in case and core.

X5 MA-2073

Plate AR37

Some banding in case and core.

X5 MA-2074

Plate AR38

Junction line between hard face and core evident. No pronounced banding. Indication of small defect near junction of hard surface layer and steel base.

X5 MA-2075

Plate AR39

Pronounced banding is evident in the steel base while the hard surface is quite uniform.

X5 MA-2076

Figure 6

Figure 7

Nonmetallic Inclusions

a. Typical nonmetallic inclusions in the low carbon rear face of plates AR30, AR35, AR36, AR37, AR38, and AR39.

Unetched X100 MA-3393

b. Typical elongated nonmetallic inclusions in the high carbon hard surface layer on plates AR36, AR37, and AR38.

Unetched X100 MA-3397

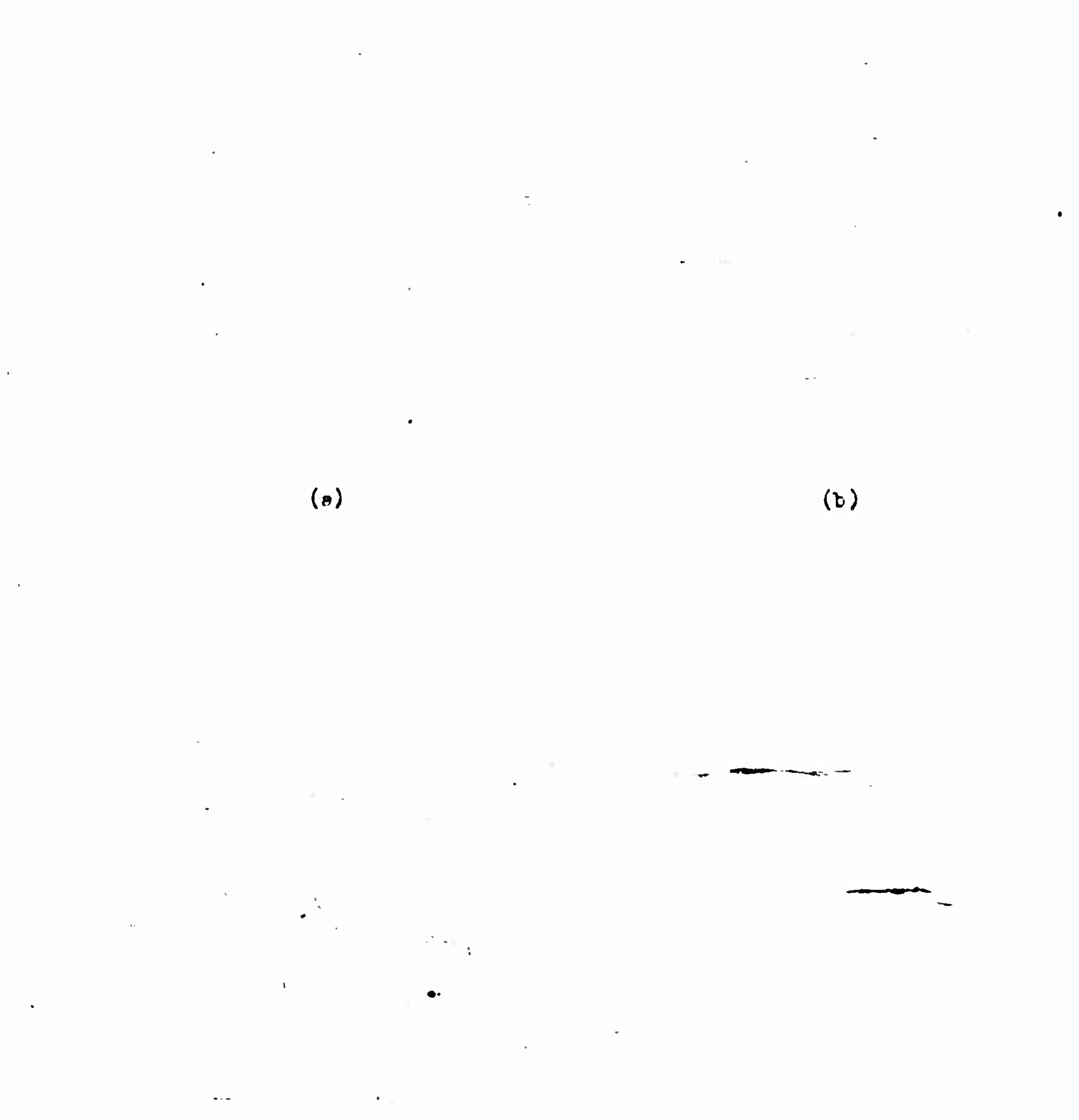
c. Typical elongated nonmetallic inclusions in the high carbon hard surface layer on plate AR39.

Unetched X100 MA-3996c

d. Typical elongated nonmetallic inclusions about .15" below surface of hard surface of plate AR35.

Unetched X100 MA-3402

Figure 7



(a) (b)

(c) (d)

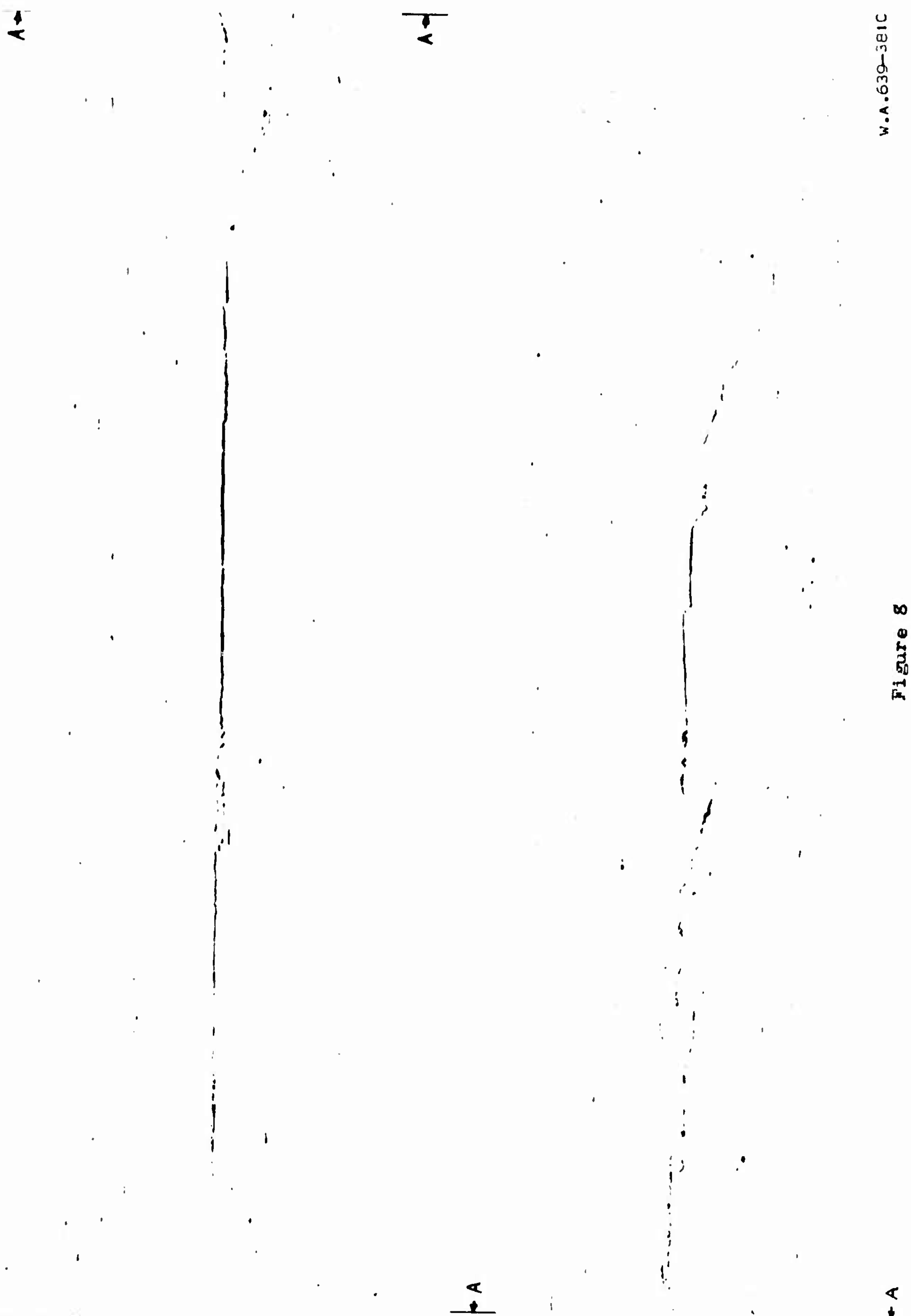
W.A. [illegible]

Figure 8

Nonmetallic Inclusions

a. Panorama of inclusion-crack system found in high carbon layer of plate AR-39. The system extends for .15". It runs almost parallel to the plate surface, beginning at .04" below the surface.

Unetched X100 MA-3388a,b,c,d,e



W.A.639-381C

Figure 8

Figure 9

Microstructure

a. Typical microstructure of hard surface layer of plate AR30.

Etched in Vilella's Reagent X100 MA-3163

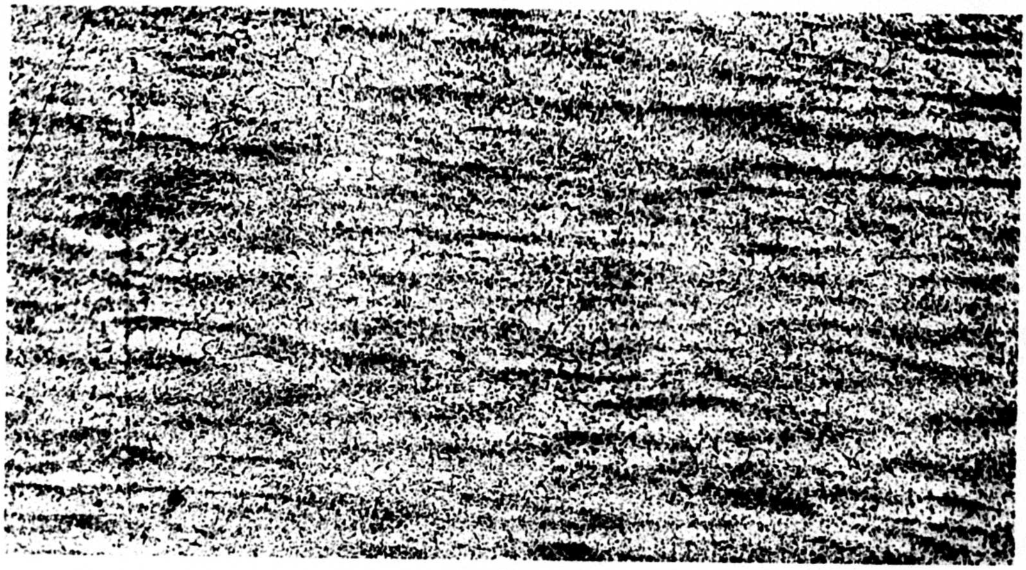
b. Typical structure of base metal side of junction between base metal and top layer of plate AR30.

Etched In Vilella's Reagent X100 MA-3161

c. Typical microstructure of low carbon steel base of plate AR30.

Etched in Vilella's Reagent X100 MA-3162

Figure 9



(a)

(b)

(c)

W.A.639-3011

Figure 10

Microstructure

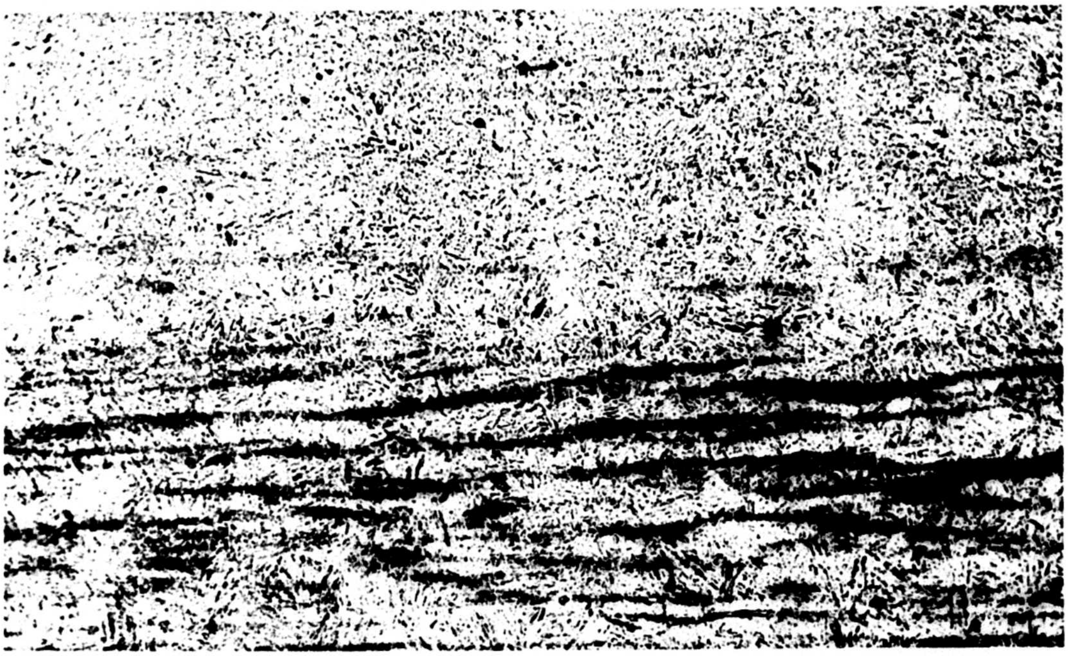
a. Microstructure of junction of hard case and soft back of another section in Plate AR30.

Etched in Vilella's Reagent	X100	MA-3166

b. Same sample as in a.

Etched in Marble's Reagent	X100	MA-3178

Figure 10



Junction Line

(a)

Junction Line

(b)

W.A.639-3822

Figure 11

Microstructure

a. Microstructure of hard surface of Plate AR30, 0.7 mm. below surface.

Etched in Marble's Reagent X1000 MA-3172

b. Same as above, 1.7 mm. below surface.

Etched in Marble's Reagent X1000 MA-3176

c. Same as above, 5.4 mm. below surface.

Etched in Marble's Reagent X1000 MA-3174

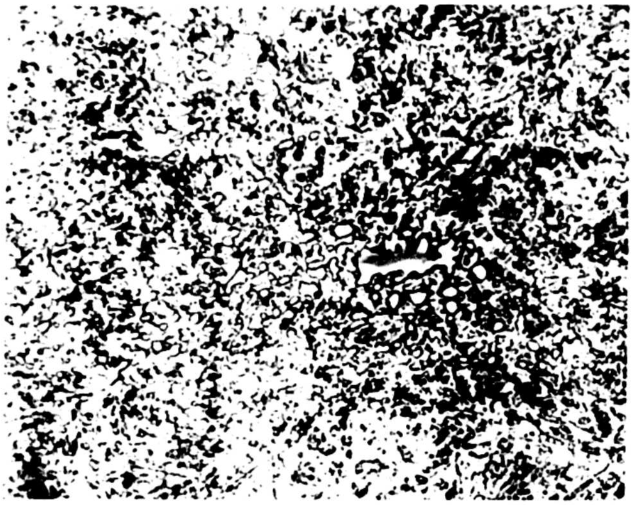
d. Same as above, 7.8 mm. below surface. Upper layer side of junction.

Etched in Marble's Reagent X1000 MA-3173

e. Same as above. Microstructure of steel base.

Etched in Marble's Reagent X1000 MA-3175

Figure 11

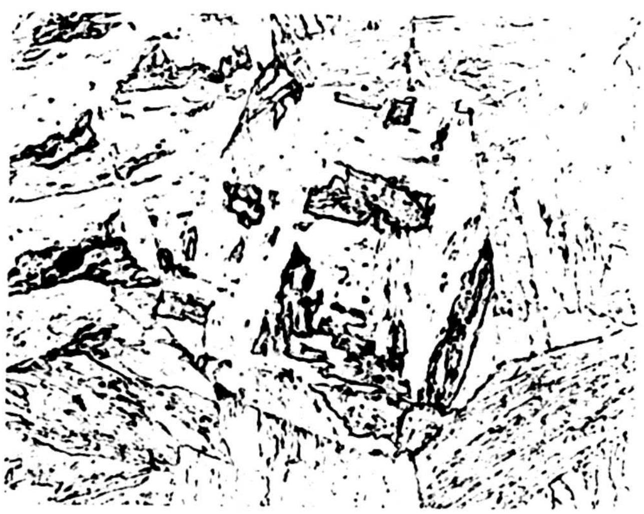


(a)

(b)

(c)

(d)



(e)

W.A.630-3801

Figure 12

Microstructure

Plate AR35

a. Microstructure of junction between hard and soft layers at approximately the center of the junction zone.

Etched in Vilella's Reagent X100 MA-3430

b. Same plate as above showing soft layer side of junction zone.

Etched in Vilella's Reagent X100 MA-3431

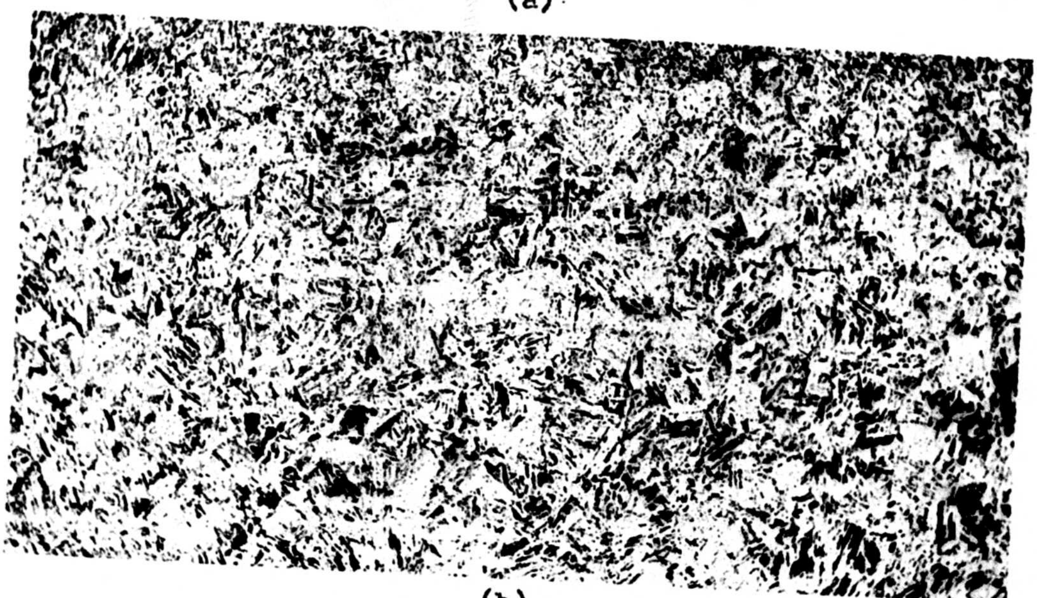
c. Same plate as above showing structure of steel base.

Etched in Vilella's Reagent X100 MA-3433

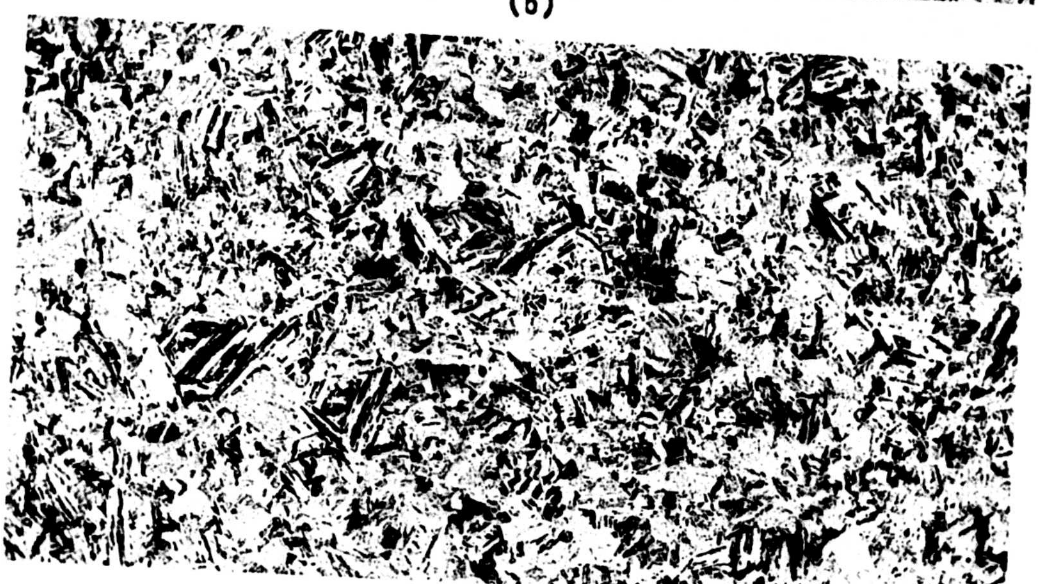
Figure 12

Junction Line

(a)



(b)



(c)

W.A.639—381[illegible]

Figure 13

Microstructure

Plate AR35

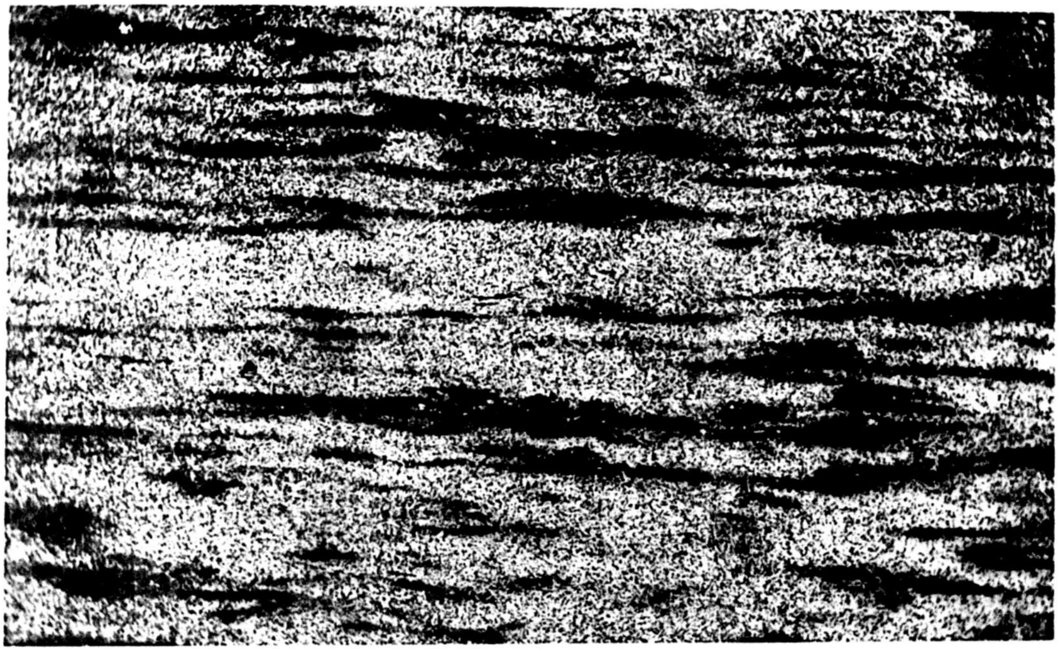
a. Typical banded structure found in hard surface layer.

Etched in Vilella's Reagent X100 MA-3434

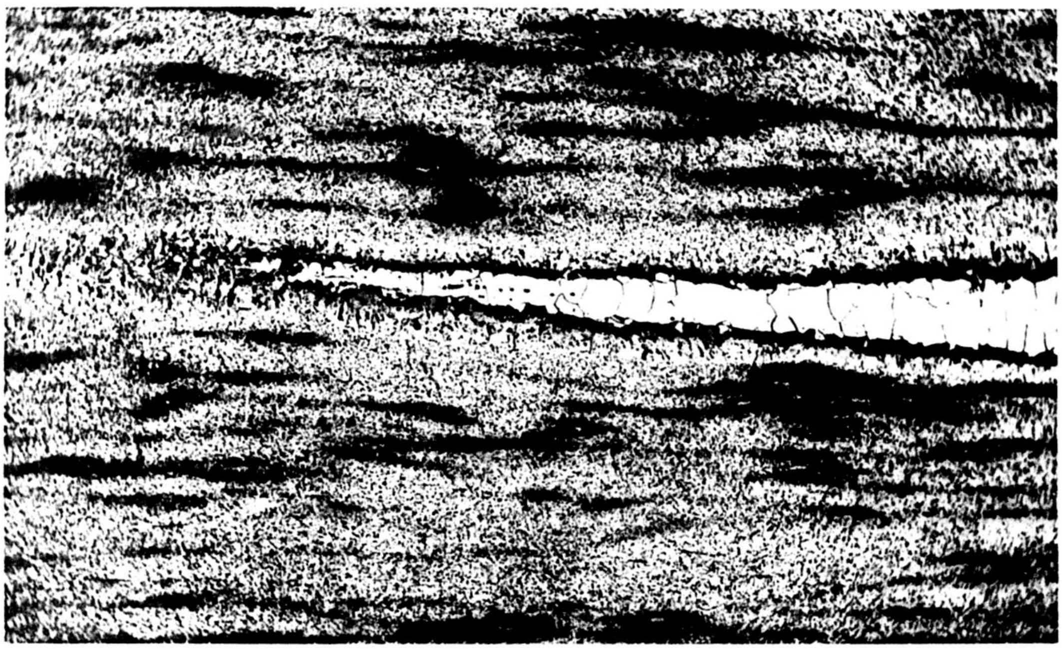
b. Showing ferrite streak in hard surface layer.

Etched in Vilella's Reagent X100 MA-3437

Figure 13



(a)



(b)

W.A.630-3815

Figure 14

Microstructure

a. Typical microstructure of hard surface layer of plates AR37 and AR38. Note banding and grain boundaries.

Etched in Vilella's Reagent X100 MA-3428

b. Typical microstructure of junction zone between hard surface and steel base of plates AR37 and AR38.

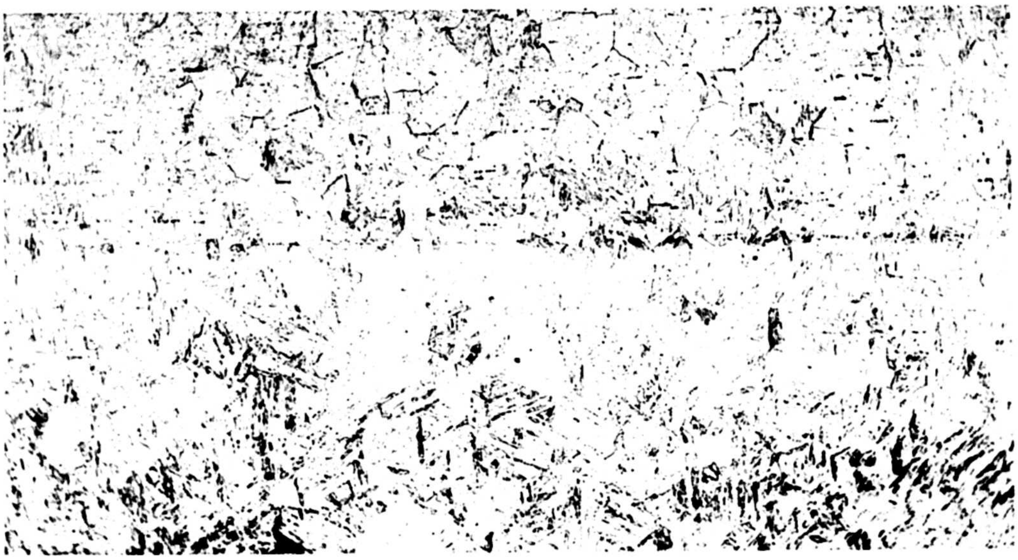
Etched in Vilella's Reagent X100 MA-3425

c. Typical microstructure of steel base of plates AR37 and AR38.

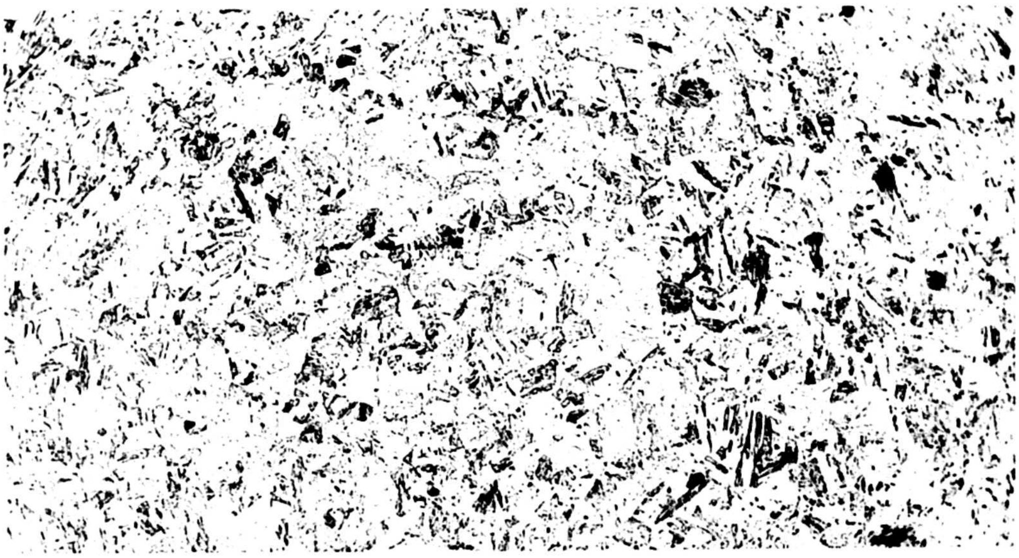
Etched in Vilella's Reagent X100 MA-3427

Figure 14

(a)



(b)



(c)

W.A.[illegible]

Figure 15

Microstructure

a. Typical microstructure of hard surface of plates AR36 and AR39.

Etched in Vilella's Reagent X100 MA-3424

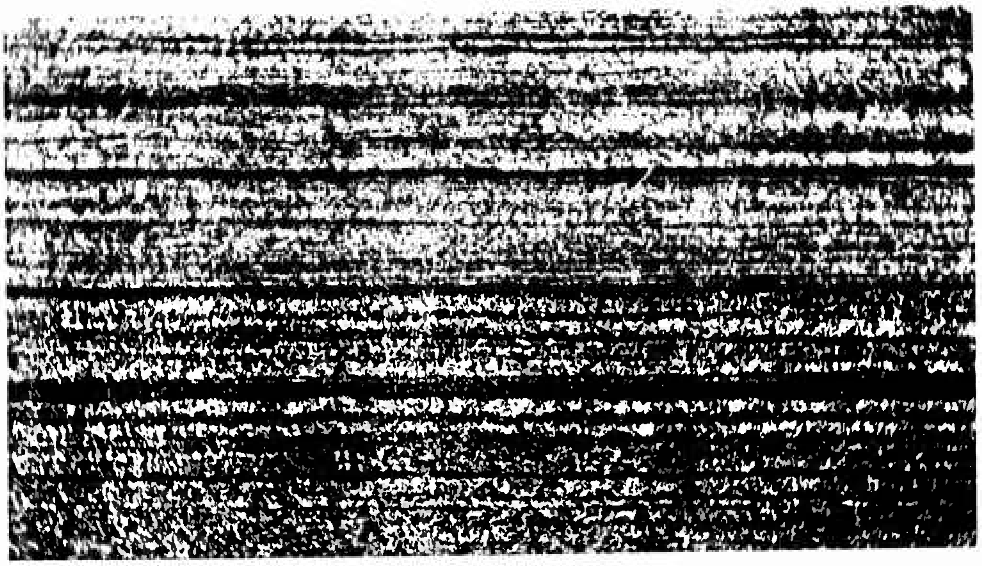
b. Typical microstructure of junction of hard surface and soft back in plates AR36 and AR39.

Etched in Vilella's Reagent X100 MA-3421

c. Typical microstructure of steel base in plates AR36 and AR39.

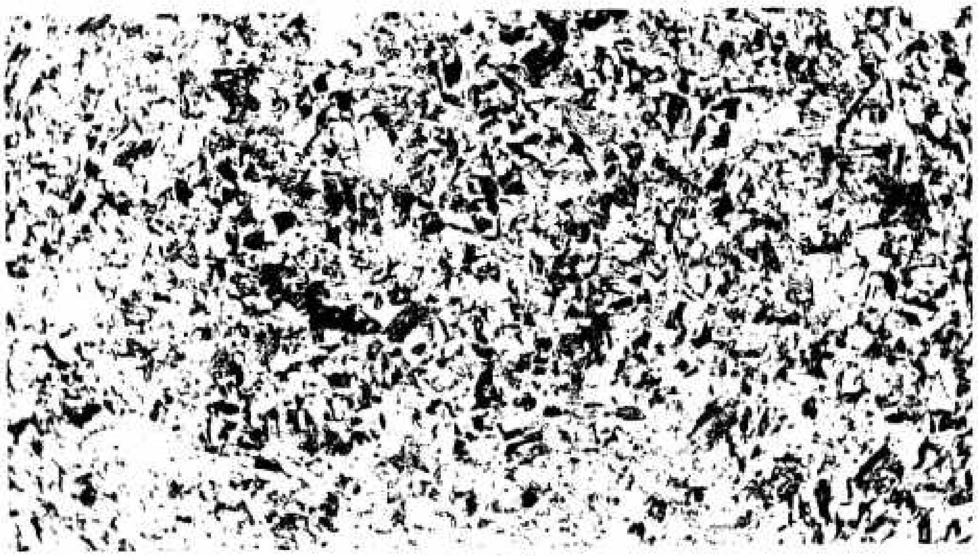
Etched in Vilella's Reagent X100 MA-3423

Figure 15



(a)

(b)



(c)

Figure 16

Microstructure

Plate AR30

a. Bands of carbides in hard surface layer.

Etched in Murakami's Reagent X1000 MA-3188

b. Another area as in "a". Evidence of grain boundary carbide.

Etched in Murakami's Reagent X1000 MA-3191

Plate AR35

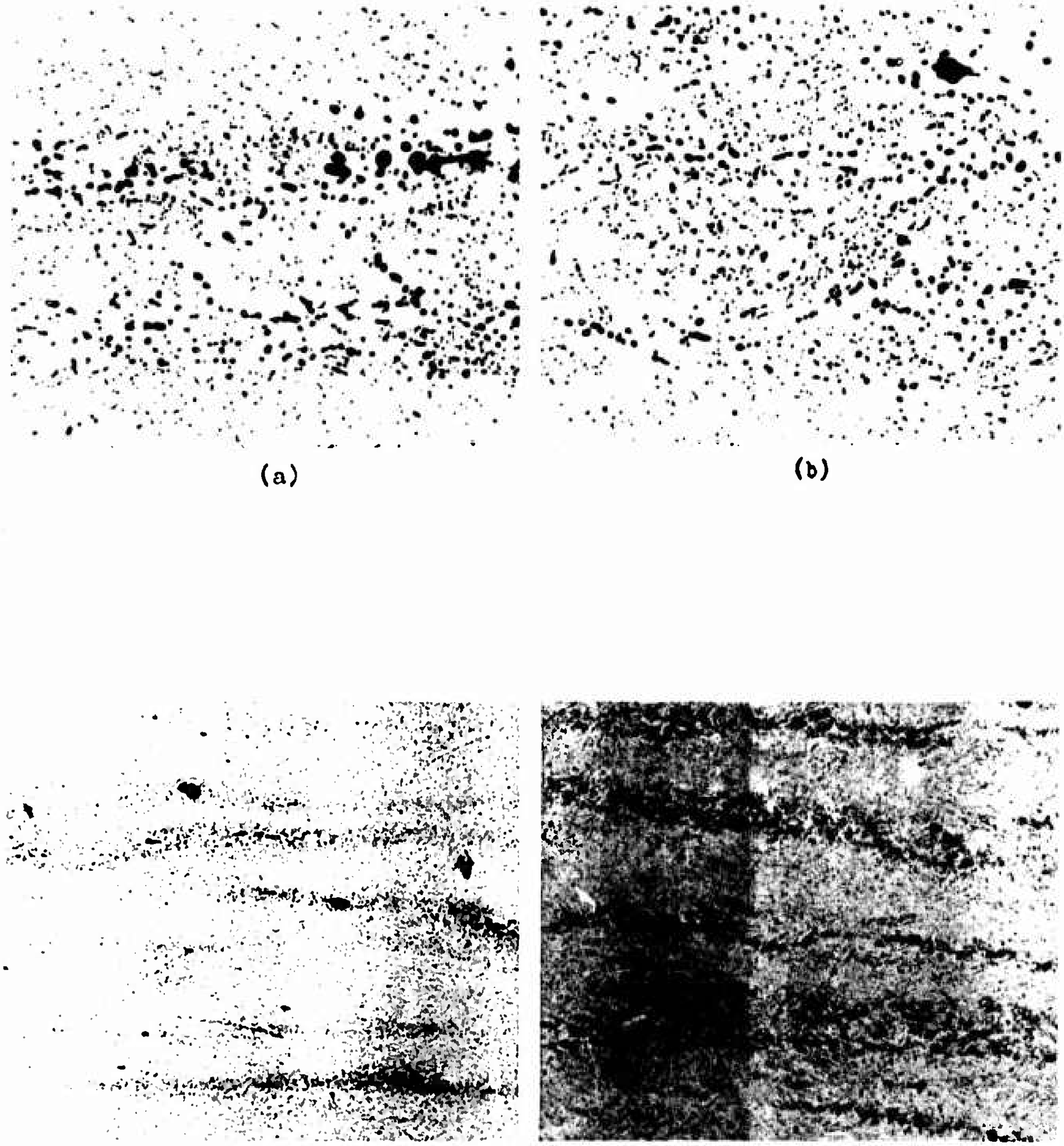
c. Bands of carbide in hard surface layer.

Etched in Murakami's Reagent X250 MA-3416

d. Bands of carbides in soft steel base of plate. The dark globules are etched delta ferrite.

Etched in Murakami's Reagent X250 MA-3417

Figure 16



(a) (b)

(c) (d)

W.A.639-3818

Figure 17

Carbide Distribution

Plate AR35

a. Grain boundary carbides in hard surface layer.
Etched in Murakami's Reagent X1000 MA-3418

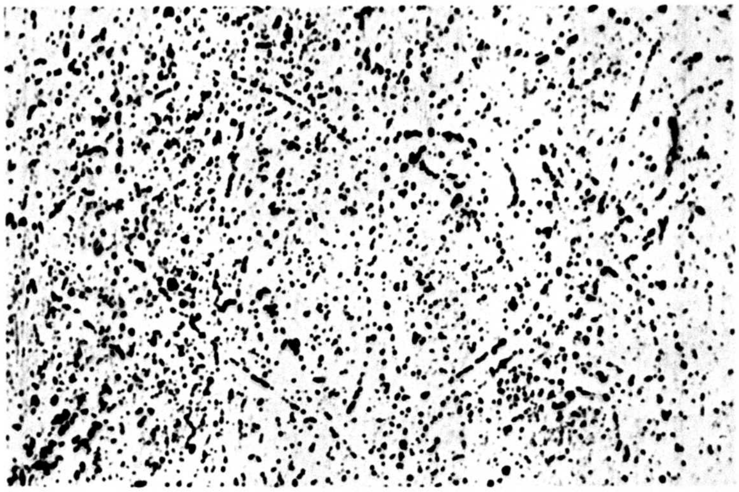
b. Grain boundary carbides in center of junction zone between hard surface layer and soft back of plate.

Etched in Murakami's Reagent X1000 MA-3420

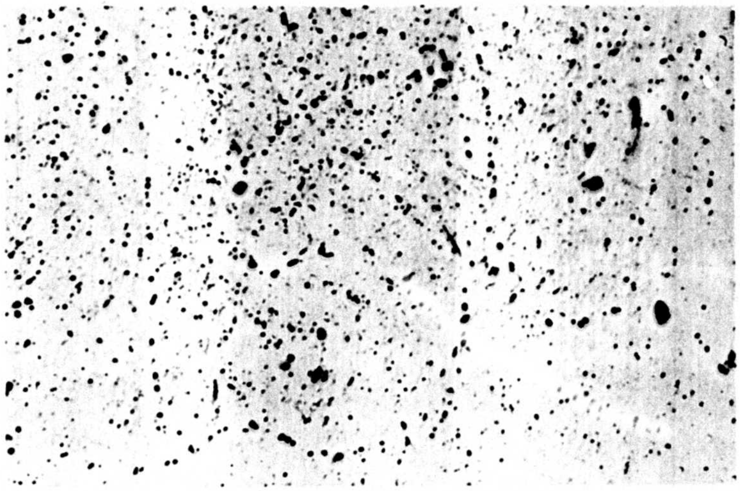
c. Carbides in steel base of plate. The dark globules are etched delta ferrite.

Etched in Murakami's Reagent X1000 MA-3419

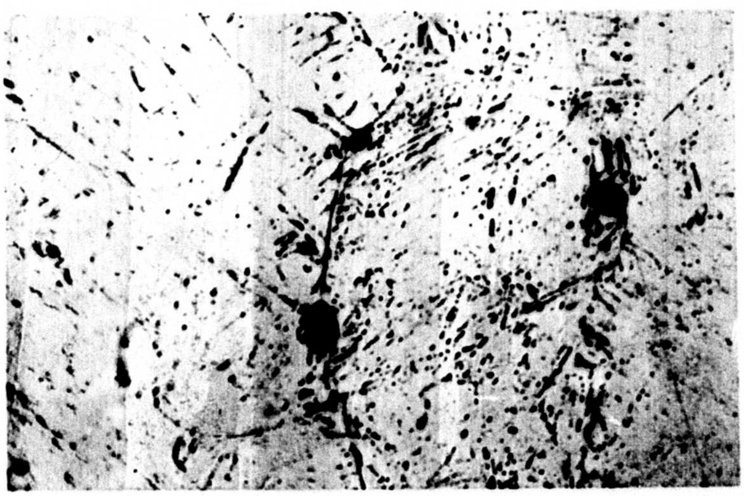
Figure 17



(a)



(b)



(c)

W.A.639-3819

Figure 18

Carbide Distribution

a. Typical bands of carbides in the hard surface layer of AR39, including the prominent band which runs parallel to the plate surface, midway between the plate surface and center of the junction zone. The inclusion stringer which begins the inclusion-crack system occurs in the band. (The stringer has been attacked by the etch.) The carbide distribution in the hard surface layer of Plate AR36 is the same as illustrated by the photomicrograph.

Etched in Murakami's Reagent X250 MA-3415

b. Typical bands of carbides in hard surface layers of Plates AR37 and AR38.

Etched in Murakami's Reagent X250 MA-3412

c. Typical grain boundary carbide found in the center of junction zone of hard surface and soft back of Plates AR36, AR37, AR38, and AR39.

Etched in Murakami's Reagent X1000 MA-3411

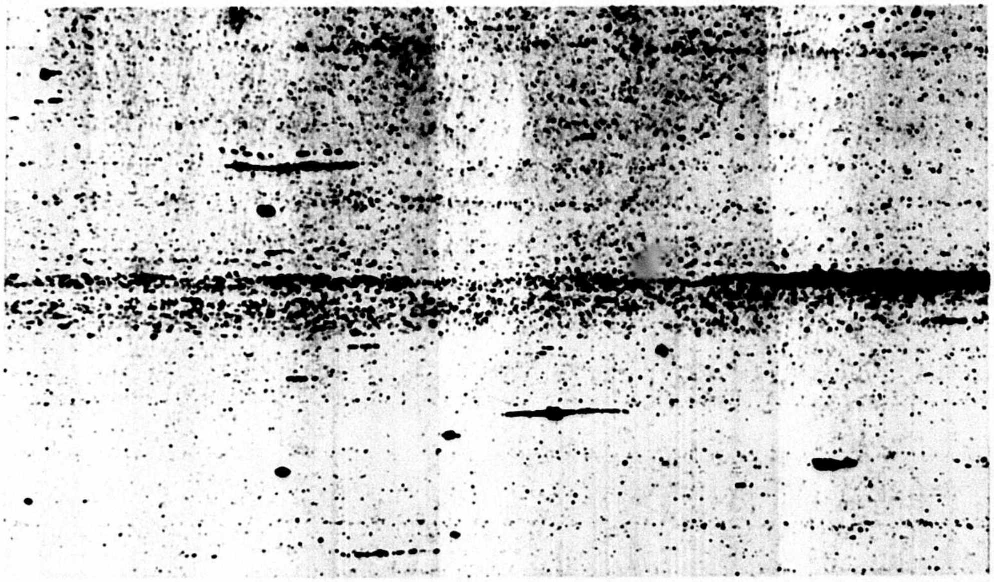
d. Typical microstructure of soft steel bases of Plates AR36, AR37, AR38, and AR39. Black globules are etched delta ferrite.

Etched in Murakami's Reagent X1000 MA-3410

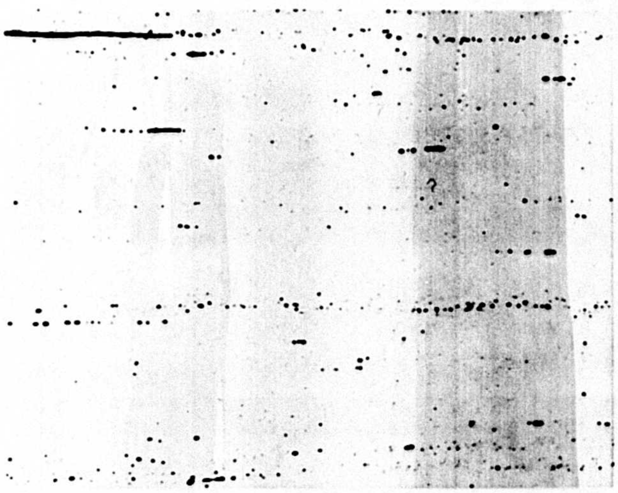
e. Typical grain boundary carbide found in the hard surface layers of Plates AR37 and AR38.

Etched in Murakami's Reagent X1000 MA-3415

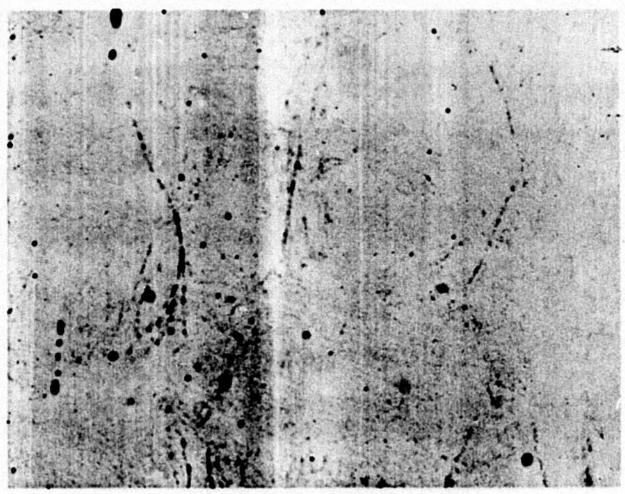
Figure 18



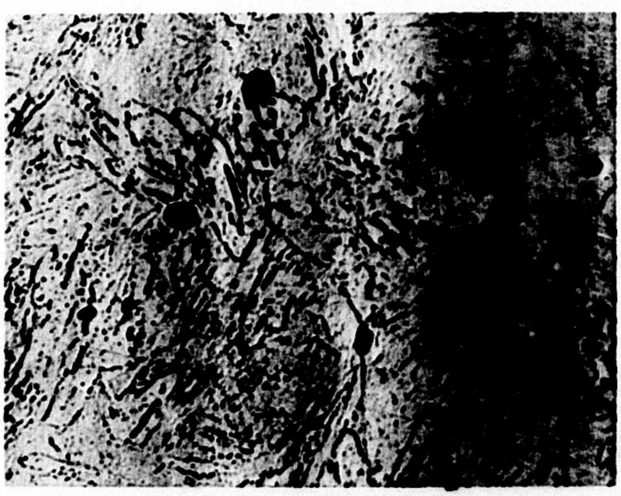
(a)



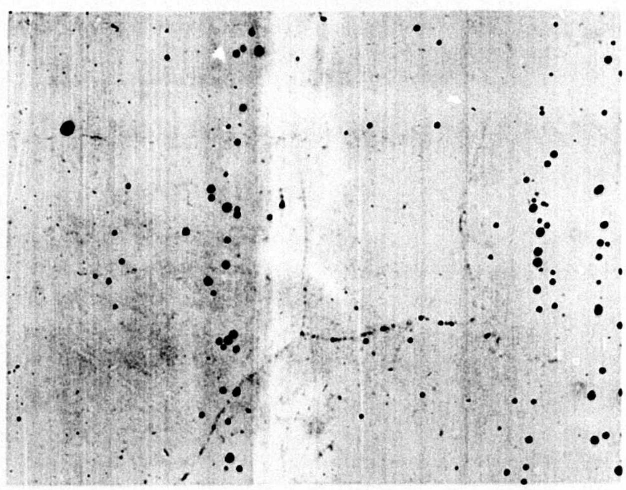
(b)



(c)



(d)



(e)

W.A.639-3820

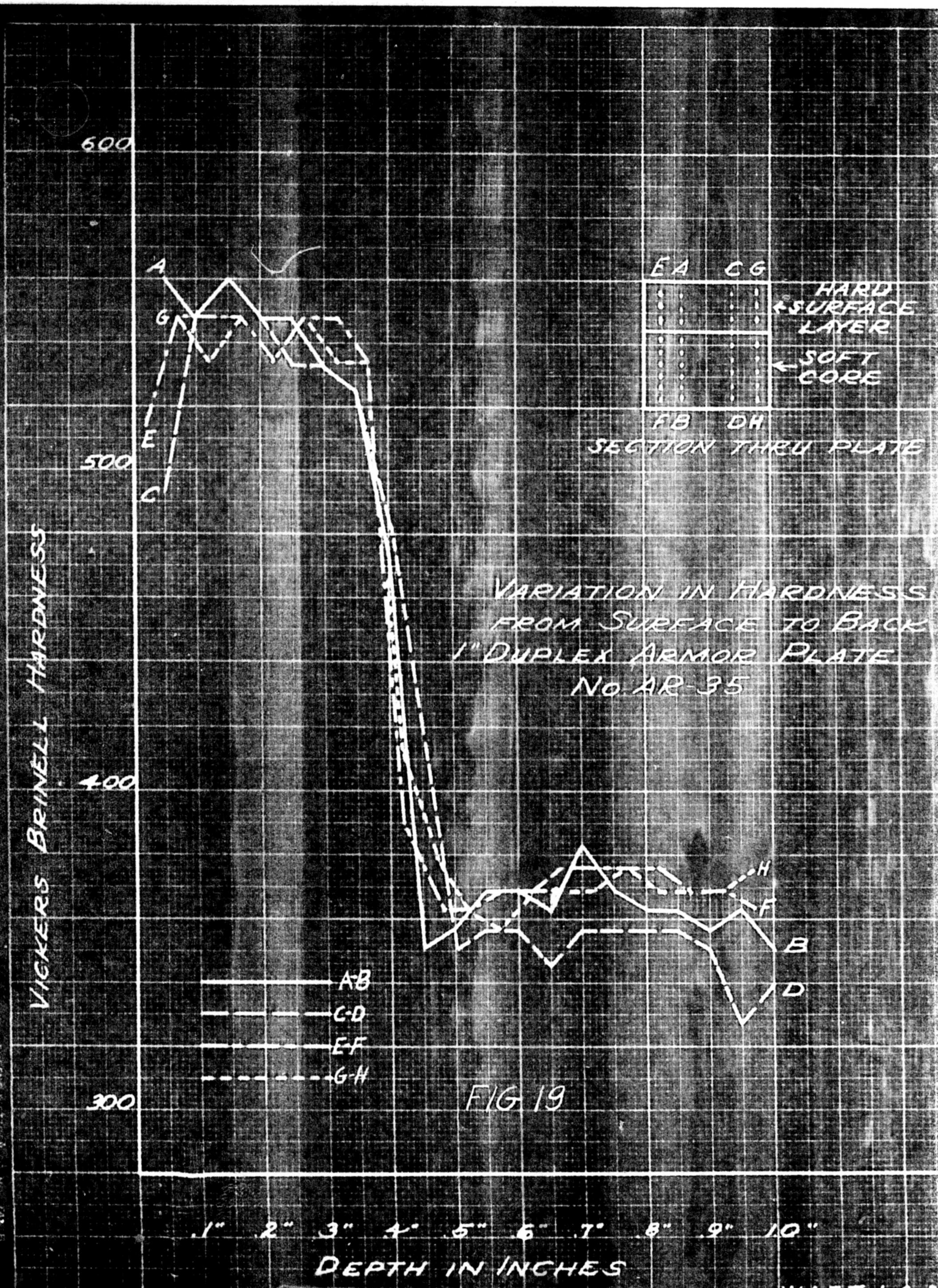


FIG 19

W.A.F.T.J. 9-2

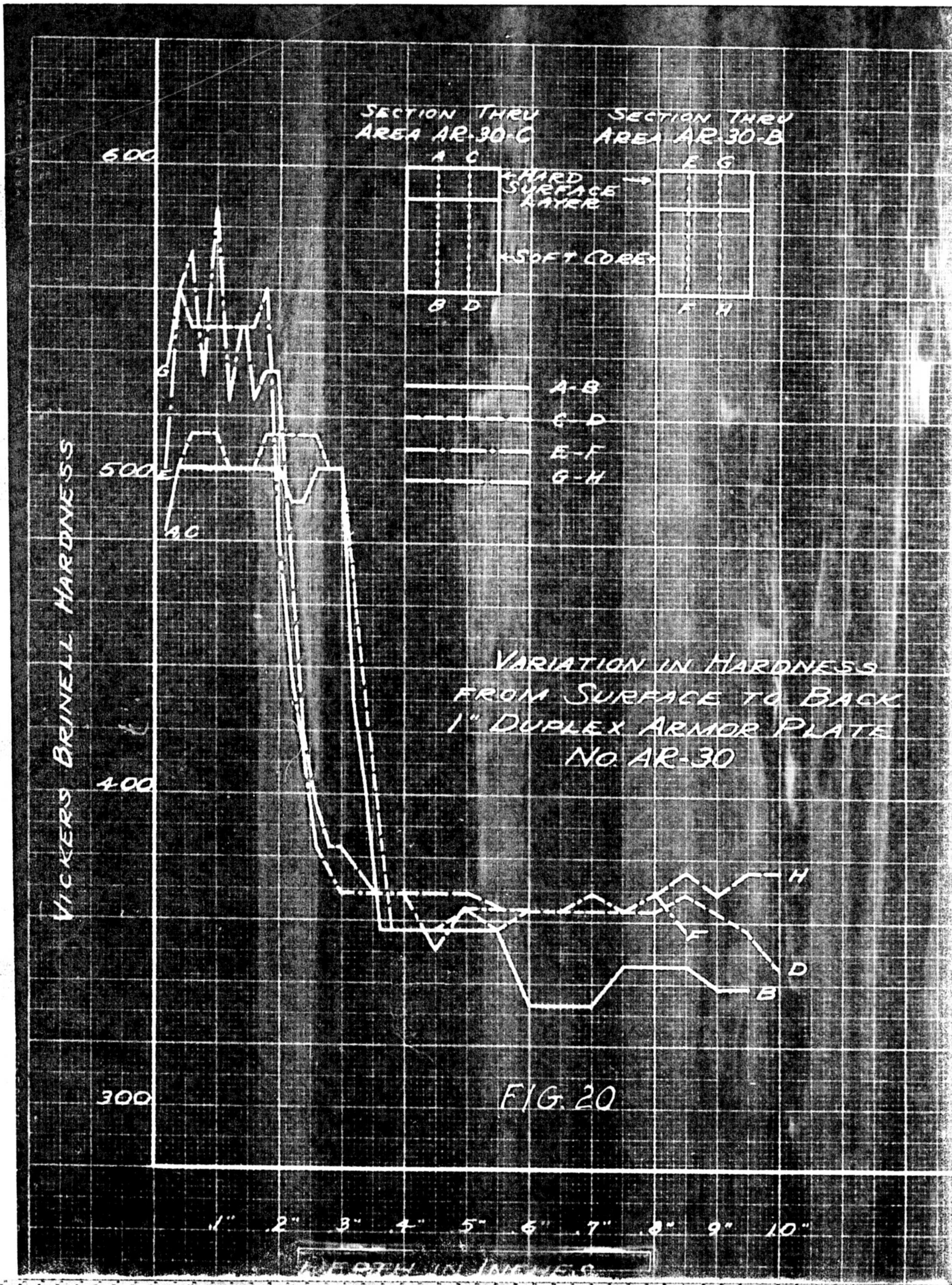

SECTION THRU
AREA AR-30-C
A C
B D
HARD SURFACE LAYER
SOFT CORE
SECTION THRU
AREA AR-30-B
E G
F H
A-B
C-D
E-F
G-H
VARIATION IN HARDNESS
FROM SURFACE TO BACK
1" DUPLEX ARMOR PLATE
NO. AR-30
VICKERS BRINELL HARDNESS
600
500
400
300
.1" .2" .3" .4" .5" .6" .7" .8" .9" 1.0"
DEPTH IN INCHES

FIG. 20

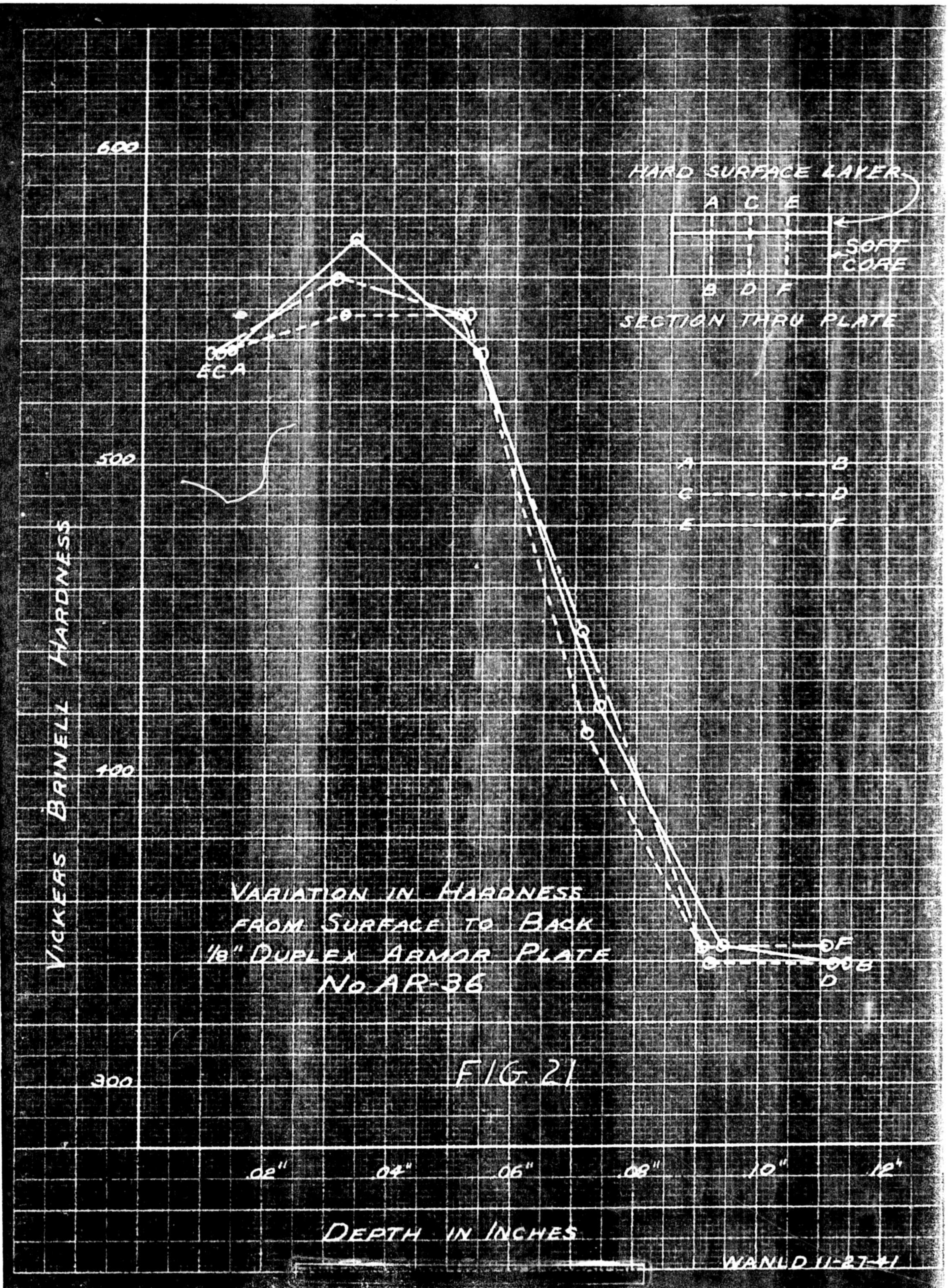

VARIATION IN HARDNESS
FROM SURFACE TO BACK
1/8" DUPLEX ARMOR PLATE
No AR-36
HARD SURFACE LAYER
SOFT CORE
SECTION THRU PLATE
A C E
B D F
VICKERS BRINELL HARDNESS
DEPTH IN INCHES
600
500
400
300
.02"
.04"
.06"
.08"
.10"
.12"
WANLD 11-27-41

FIG. 21

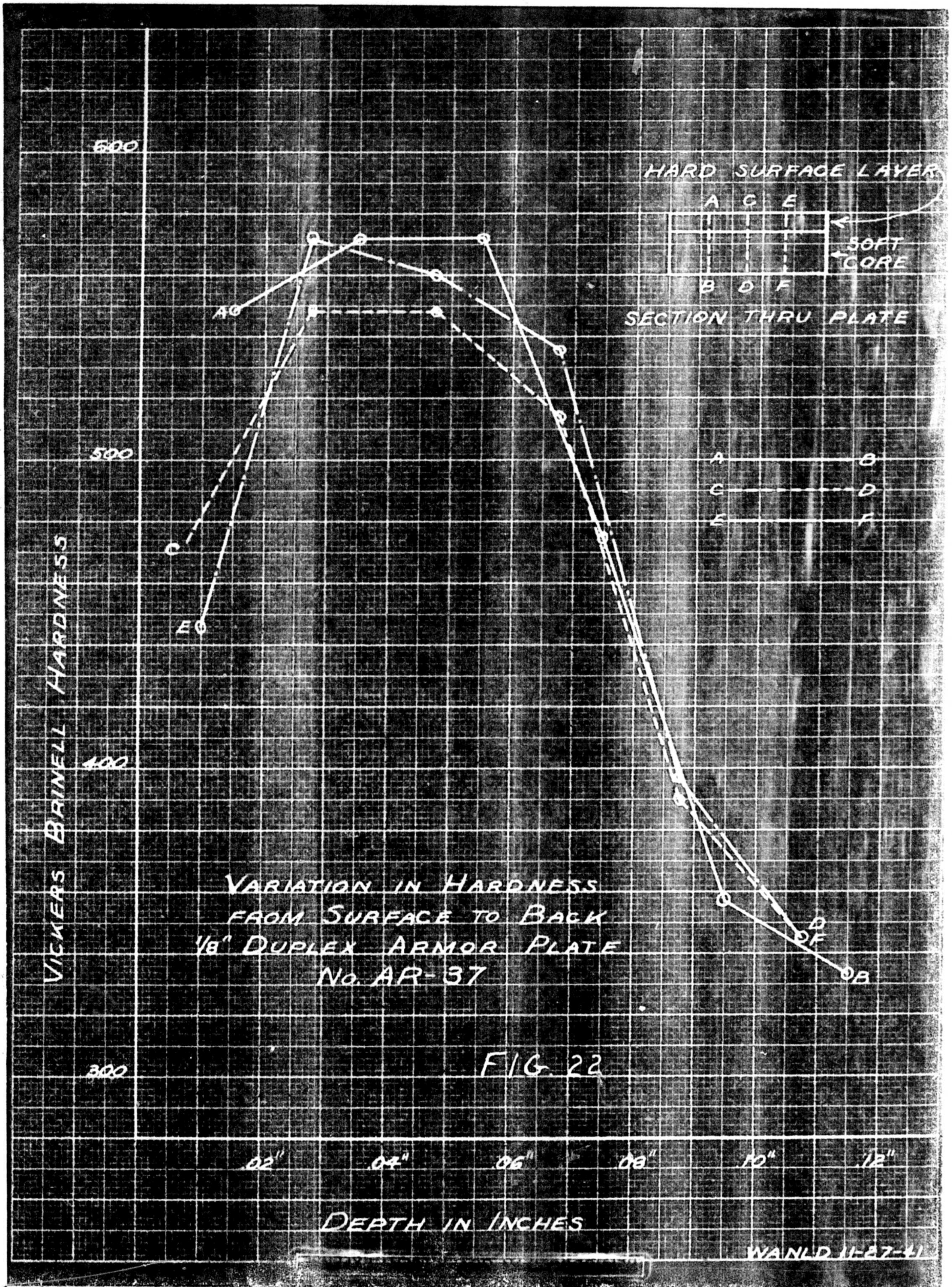

VARIATION IN HARDNESS
FROM SURFACE TO BACK
1/8" DUPLEX ARMOR PLATE
No. AR-37
VICKERS BRINELL HARDNESS
600
500
400
300
DEPTH IN INCHES
.02"
.04"
.06"
.08"
.10"
.12"
HARD SURFACE LAYER
A C E
SOFT CORE
B D F
SECTION THRU PLATE
A B
C D
E F
WANLD 11-27-41

FIG. 22

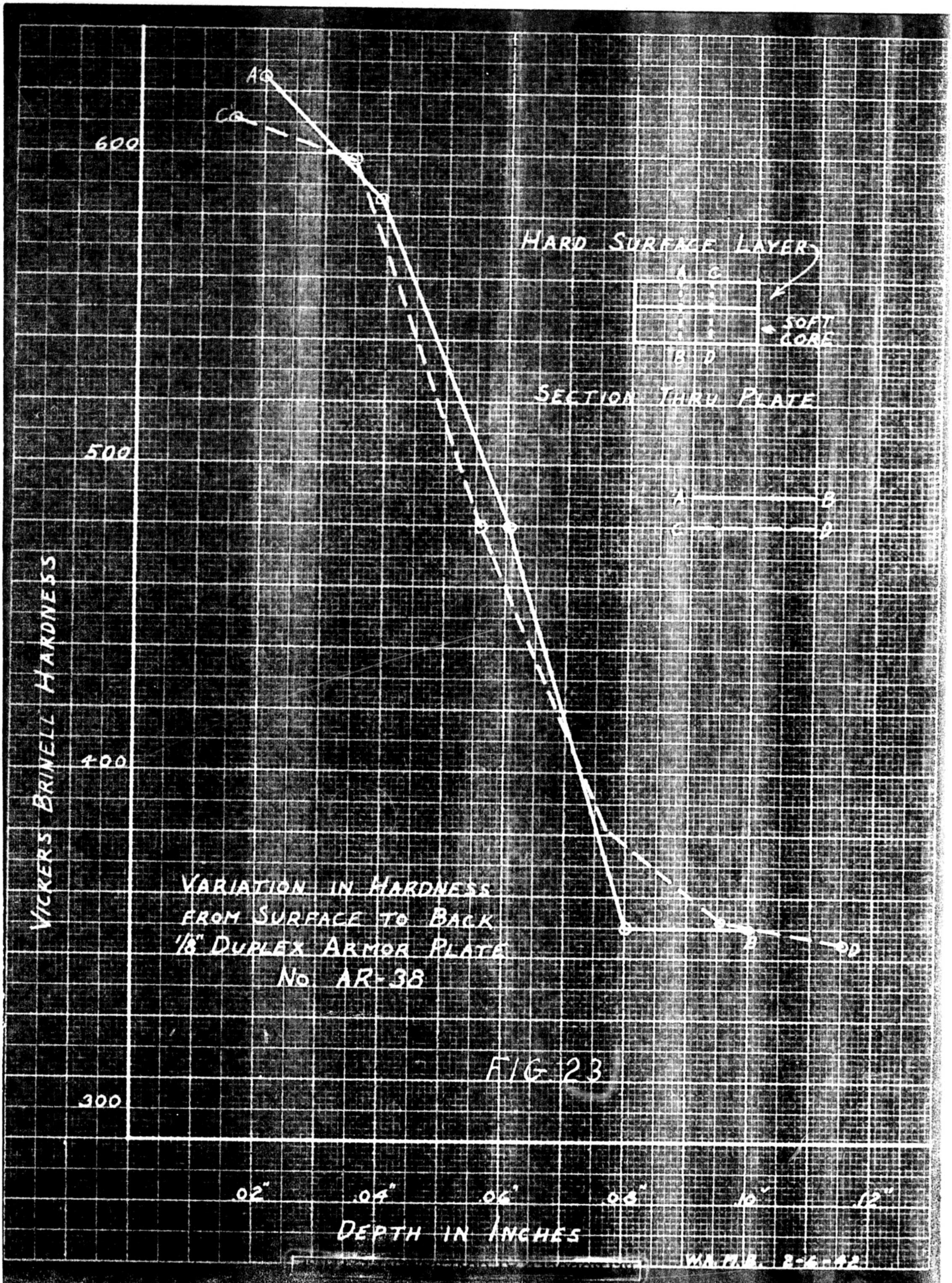
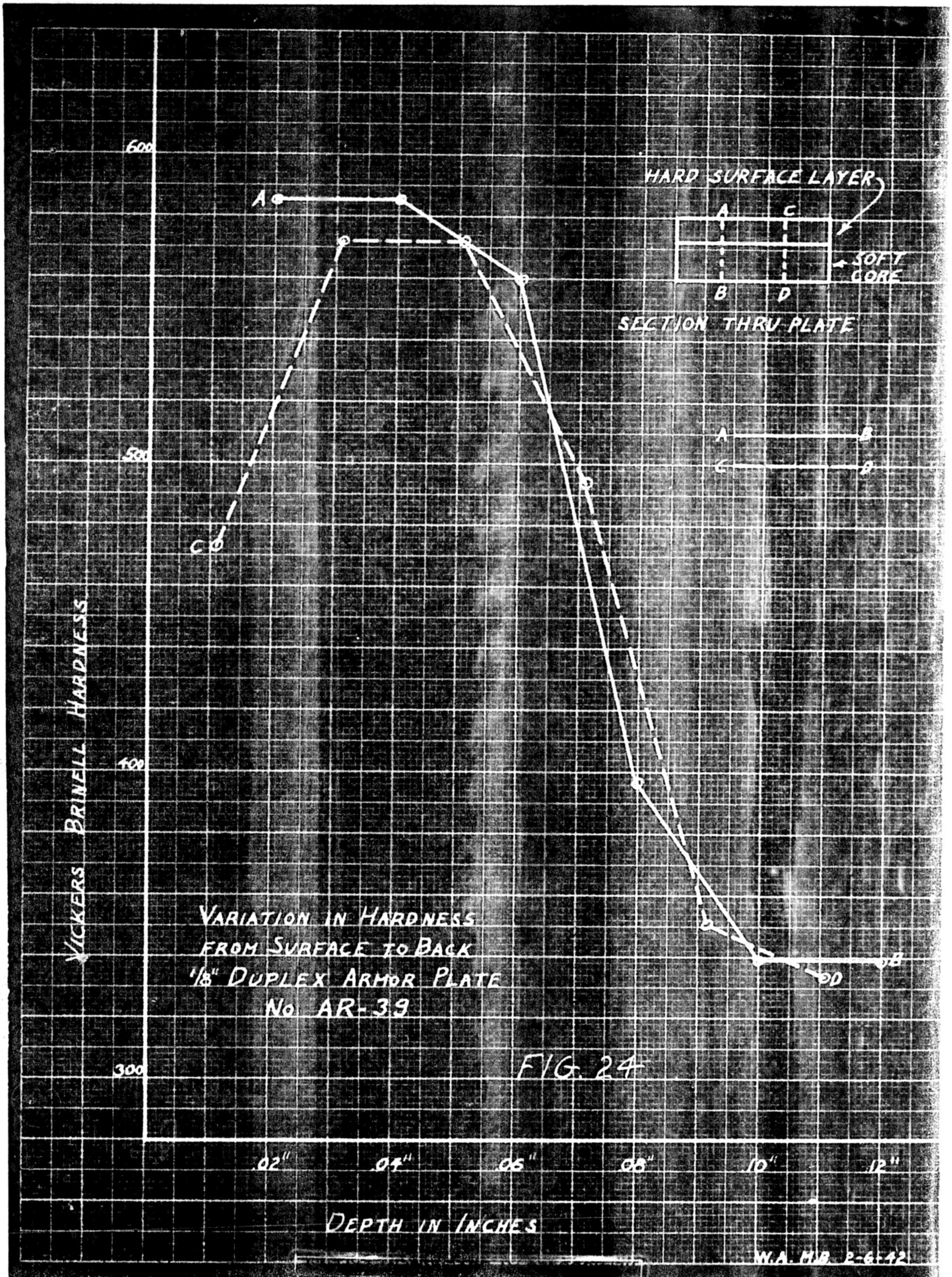

A
C
600
500
400
300
HARD SURFACE LAYER
A C
B D
SOFT CORE
SECTION THRU PLATE
A B
C D
VICKERS BRINELL HARDNESS
VARIATION IN HARDNESS
FROM SURFACE TO BACK
1/8" DUPLEX ARMOR PLATE
No. AR-38
B
D
.02"
.04"
.06"
.08"
.10"
.12"
DEPTH IN INCHES
W.H.M.B. 2-6-42

FIG 23



VICKERS BRINELL HARDNESS
600
500
400
300
A
B
C
D
HARD SURFACE LAYER
SOFT CORE
SECTION THRU PLATE
VARIATION IN HARDNESS
FROM SURFACE TO BACK
1/8" DUPLEX ARMOR PLATE
No. AR-39
.02"
.04"
.06"
.08"
.10"
.12"
DEPTH IN INCHES
W.A. M.B. 2-6-42

FIG. 24

APPENDIX A

JHF:ms

COPY

W.A. 470.1/5178
O.O. 470.1/1069

WAR DEPARTMENT

OFFICE OF THE CHIEF OF ORDNANCE

WASHINGTON

July 10, 1941

Subject: Composite Steels

To: Commanding General
Watertown Arsenal
Watertown, Mass.

1. The Allegheny-Ludlum Steel Corporation is producing a type of composite sheet and plate which differs from methods used heretofore. This process is known as "Pluramelt" and was developed by the M. W. Kellogg Company of New Jersey. In this connection there is attached a copy of a memorandum explaining this process in some detail.

2. It is desired that certain members of the Ordnance Department visit the Allegheny-Ludlum Steel Corporation Brackenridge plant to inspect this process and develop its possibilities in ordnance uses. This meeting has been tentatively set for July 21.

3. It is requested that Lt. Col. Ritchie be present at this meeting.

By order of the Chief of Ordnance:

G. M. BARNES
Brig. Gen., U. S. Army
Asst., Chief of Industrial Service
Engineering

1 Incl.
copy of memorandum

COPY

COPY

WAR DEPARTMENT

OFFICE OF THE CHIEF OF ORDNANCE

WASHINGTON

June 25, 1941 JGD/mcl

MEMORANDUM FOR: General C. M. Wesson

SUBJECT: Pluramelt

1. The Pluramelt process for producing composite plate was developed by the M. W. Kellogg Company of New Jersey. It was developed with the idea of producing oil cracking still chambers and chemical reaction vessels consisting of mild steel coated with stainless steel or other corrosion resisting alloys so that the bulk of the weight of the vessel consisted of low-cost mild steel while the surface exposed to the corrosive medium was an alloy.

2. To achieve this result a long series of research experiments were conducted by Dr. Hopkins of the Kellogg research staff and he evolved the present Pluramelt process, the patents for which were then purchased by the Allegheny Ludlum Steel Corporation for the exclusive manufacture of this product.

3. To make a slab of armor plate, for example, a rolled slab of steel would be placed in the Pluramelt apparatus so that the edge or surface of the slab to be covered with the hard-surface coating would be exposed to the action of an electrode. This electrode is fed through a series of rollers which form the electrode from a steel strip into a hollow tube. Inside the tube is fed the alloying constituent in granulated form, such as ferro-chrome, nickel, ferro-vanadium, etc. These are fed in the proper proportions and as they reach the bottom of the electrode where the electrode arc is formed with the steel slab they are melted by the arc and literally welded to the surface of the steel slab. The electrode moves back and forth across the face of the slab and puts on a half an inch, an inch or more, of the new hard metal by actually forming a welded bond with the parent surface of the slab. When the surface has been completely covered another surface opposite to it can be

COPY

covered or not as required. In any event, the slab is then one solid piece consisting of the heavy section of the tough backing up steel which came from the blooming mill, on the surface of which has been welded a harder face which can be of any analysis required. The slab is then sent to the rolling mill for further reduction and the hard surface is reduced in thickness by the rolling in the same proportion of the entire slab. Thus, light, medium, or heavy armor could be produced with any analysis of the backing up material and any analysis of the hardened surface material could be used.

4. The main advantage of the Pluramelt Process over any other method of bonding two unlike metals together is the fact that the electric welding process is a complete union between the two types and gives the so-called tapered analysis from the center of the slab to the hard face. This is caused by the flow of the alloying metal in the welding and results in very desirable characteristics on the finished plate.

J. G. Detwiler
1st Lt., Ord. Dept.
Assistant